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# DEVELOPMENT OF A FIELD MANUAL FOR THE CHARACTERIZATION OF SPRAY FROM SMALL AIRCRAFT

Prepared by

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Prepared for

Forest Service
U. S. Department of Agriculture
Equipment Development Center
Missoula, Montana 59801

and

Methods Application Group
Davis, California

Final Report Under Contract No. 26-3694

December 1976

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TABLE OF CONTENTS


| Section | Title | Page |
|---|---|---|
| | ACKNOWLEDGEMENTS | 1 |
| 1 | INTRODUCTION | 2 |
| 2 | EQUIPMENT REQUIRED FOR FIELD CHARACTERIZATION OF SPRAY FROM SMALL AIRCRAFT | 4 |
| | 2.1 Grid Layout and Sampling Equipment | 4 |
| | 2.2 Equipment for Field Analysis of Spray Deposit Cards | 8 |
| | 2.3 Equipment for Field Laboratory Analysis | 10 |
| 3 | DESIGNING THE SAMPLING GRID: OPERATIONAL CONSIDERATIONS | 13 |
| | 3.1 Design of the Sampling Grid | 13 |
| | 3.2 Operational Considerations | 22 |
| 4 | FIELD CHARACTERIZATION OF THE SPRAY DISSEMINATION SYSTEM | 31 |
| | 4.1 Plastic Templates for Sizing and Counting Drops | 31 |
| | 4.2 Swath Width and Drop Density | 31 |
| | 4.3 Field Estimation of Volume Median Diameter | 36 |
| 5 | FIELD LABORATORY CHARACTERIZATION OF THE AIRCRAFT SPRAY DISSEMINATION SYSTEM | 41 |
| | 5.1 Drop Density Distribution in the Swath | 41 |
| | 5.2 Determination of the Swath Drop-Size Distribution, Mass Median, Average Mass and Number Mean Diameters | 45 |
| | 5.3 Estimation of Spray System Deposition, Deposition Efficiency (Mass Recovery) and Swath Width Based on Mass Deposition | 61 |
| | REFERENCES | 68 |

ACKNOWLEDGEMENTS

The procedures described in this manual are principally based on experience gained during the conduct of spray characterization trials at Townsend, Montana in the late spring of 1976 and from an analysis of the data obtained during these trials. Many people participated in the development of the procedures outlined in the manual. In particular, the authors gratefully acknowledge the very valuable assistance of William McIntyre (Dugway Proving Ground, Dugway, Utah) and Robert Ekblad (U. S. Forest Service, MEDC, Fort Missoula, Montana) in all phases of the work. We are also indebted to John Barry and Lynne Whitcombe, U. S. Forest Service, FI&DM Applications Group, Davis, California for their assistance in data analysis during the Townsend trials. The very helpful assistance of our colleagues W. R. Santee and A. L. Hancock during the post-trial data analysis is also gratefully acknowledged.

# SECTION 1
# INTRODUCTION

The purpose of this manual is to describe field procedures for the rapid characterization of the spray deposit from small aircraft spray systems prior to forest spray operations. The techniques described in this manual are intended to assist spray project entomologists in establishing the applicability of specific spray system characteristics to particular application problems and to assist aircraft engineers in implementing and testing the effects of field changes in aircraft spray systems intended to improve application characteristics. Techniques are described for:

- Establishing the design of a sampling grid and test plan for determining spray characteristics
- Estimating the volume median, number median and average mass diameters of the spray deposit
- Estimation of the minimum effective swath width produced by the spray equipment and the mass per unit area deposited within the swath width
- Estimation of the spray system deposit efficiency within the swath

Section 2 defines the field equipment required to accomplish the spray characterization. The development of a test plan and design of a sampling grid are discussed in Section 3. The description of field procedures for spray characterization is contained in two sections. Section 4 describes procedures for the preliminary estimation of volume median diameter and swath width immediately after an aircraft spray flight so that immediate decisions can be made regarding aircraft flight altitude,

nozzle type, nozzle configuration and other factors affecting spray deposit. Techniques for use in the field laboratory to confirm these preliminary estimates of volume median diameter and swath width and to obtain quantitative estimates of the number median diameter, average mass diameter and associated mass recovery are described in Section 5.

## SECTION 2

## EQUIPMENT REQUIRED FOR FIELD CHARACTERIZATION OF SPRAY FROM SMALL AIRCRAFT

The successful conduct of spray characterization field trials requires a relatively large amount of equipment. Because field trials are usually conducted in remote areas, most of this equipment must be acquired in advance of the trials. The necessary equipment for establishing the sampling grid, conducting the trials, and analyzing the data is listed and briefly described in this section. In some cases, equipment is identified by manufacturer or catalog number. These designations do not constitute an endorsement of the equipment, but are given to assist in identifying the type of equipment or material necessary for accomplishing the objectives of the project.

### 2.1 GRID LAYOUT AND SAMPLING EQUIPMENT

Table 2-1 lists equipment required to lay out the sampling grid and to sample the spray drops and meteorological parameters. A brief description of the intended use of the equipment is also provided in the table. More detailed descriptions of the use of the equipment are given in Section 3 below.

The sampler cards most often used in sampling spray drops containing oil-red or organic tracer dyes are 17 by 11 centimeter cards, Kromekote Cover 65 pound paper, glossy coated both sides, manufactured by the Champion Paper and Fiber Company, Hamilton, Ohio. A plastic card holder, manufactured by the General Binding Company for Missoula Equipment Development Center (MEDC, USFS), has proven very effective in field characterization trials. The card holder is designed so that several sampling cards can be placed in the holder at one time and the top card removed after a trial to expose a clean card for the next trial. The lips of the card holder are such that the effective sampling area of the exposed card is about 14 by 9 centimeters. Further information concerning other types of sampling cards and the card holders can be obtained from MEDC.

TABLE 2-1

SAMPLING AND GRID LAYOUT EQUIPMENT

| Equipment | Use |
|---|---|
| Sampler Cards | Collection of spray drops |
| Card Holders | Protection of cards (from smudging, etc.) and ease of handling |
| Collection Boxes | Contain cards and holders for disposition and collection in the field |
| Marking Pens | Marking individual sampler cards with sampler location and trial number |
| Manilla Rope and Ties, Tape Measure | Layout of sampling lines |
| Wooden and/or Metal Stakes, Sledge | Identification of sampling locations and lines |
| Smoke Grenades | Smoke plumes aid pilot in locating spray grid and director in estimating wind velocity relative to sampling layout |
| Low-Level (2-meter) Wind Direction and Speed Sensor, Recording Equipment | Continuous chart record of wind speed and direction |
| Pilot Balloons and Helium (Optional) | Vertical profiles of wind direction and speed |
| Tethersonde (Optional) | Vertical profiles of temperature, wind direction, wind speed and relative humidity |

TABLE 2-1 (Continued)

| Equipment | Use |
|---|---|
| Transit or Theodolite | Orienting sampling lines and meteorological equipment; theodolite can also be used to track pilot balloons |
| Protective Clothing and/or Large Plastic Bags | Protection of field workers and equipment in aircraft spray path |
| Communications Equipment | Communications between field crew and between field crew manager and project director |

Boxes for transporting the cards to and from the field laboratory and along the sampling lines are necessary. These boxes are conveniently constructed from plywood. Suggested inside dimensions are 13 centimeters wide, 20 centimeters deep and 36 centimeters long. A wide canvas shoulder strap attached to the ends of the box facilitates carrying the cards and card holders along the sampling lines. A small section can be added to the box for transporting marking pens, which may be required to alter the numbers identifying the sampling positions.

Manilla ropes, tape measure, stakes and sledge hammers are necessary for laying out the sampler lines. Bright tape, such as surveyor's tape, is tacked to the 3/8 inch manilla rope using hog rings or other suitable fasteners at 10-foot intervals. One-hundred foot lengths of manilla rope are conveniently handled in the field. Quarter-inch stock metal rods cut 2.5 feet in length are used to mark card positions along the sampling lines.

Smoke grenades, such as the U. S. Army Grenade, Hand M-18, with yellow or white smoke are essential in conducting field characterization trials. The smoke plumes serve to indicate the wind speed, wind direction and atmospheric diffusion conditions.

A battery operated low-level (2-meter) wind direction and speed sensor with associated strip-chart recording equipment is necessary for documenting meteorological conditions during the characterization trials and in establishing preferred wind directions at a given site prior to the trials. Recording strip-chart speeds of 3 inches per hour should be specified and changeable gears to permit chart speeds of 12 inches per hour. The Electronic Weather Station (EWS) manufactured by Climatronics Corporation, Hauppauge, New York, and equipped for measuring and recording wind speed and direction is typical of instruments meeting the above requirements. Pilot (10-gram) balloons are used to obtain vertical profiles of wind speed and direction. Continuous measurements of wind speed and direction and temperature in the vertical to heights above the planned aircraft altitude are also

TABLE 2-3

EQUIPMENT FOR FIELD LABORATORY ANALYSIS OF SPRAY DEPOSIT CARDS

| Equipment | Use |
|---|---|
| Cork Bulletin Board | Work base for sizing and counting drops |
| Large Bulletin Board Push Pins | Tacking card to bulletin board |
| Card Illumination Lamp | High-intensity illumination of counting area |
| Counting and Sizing Card Templates | Identification of card area for counting and sizing drops |
| Measuring Magnifier, Data Sheets | Counting and sizing drops |
| Pencils, Pencil Sharpeners, Grease Pencils, Cleaning Tissue, Stapler, Note Pads, Envelopes, Rubber Bands, Paper Clips | Data recording, data organization |
| Graph Paper (10 x 10 to the Centimeter and Probability x 2 Log Cycle) | Graphic data display |
| Programmable Electronic Calculator (Optional) | Mathematical calculations |

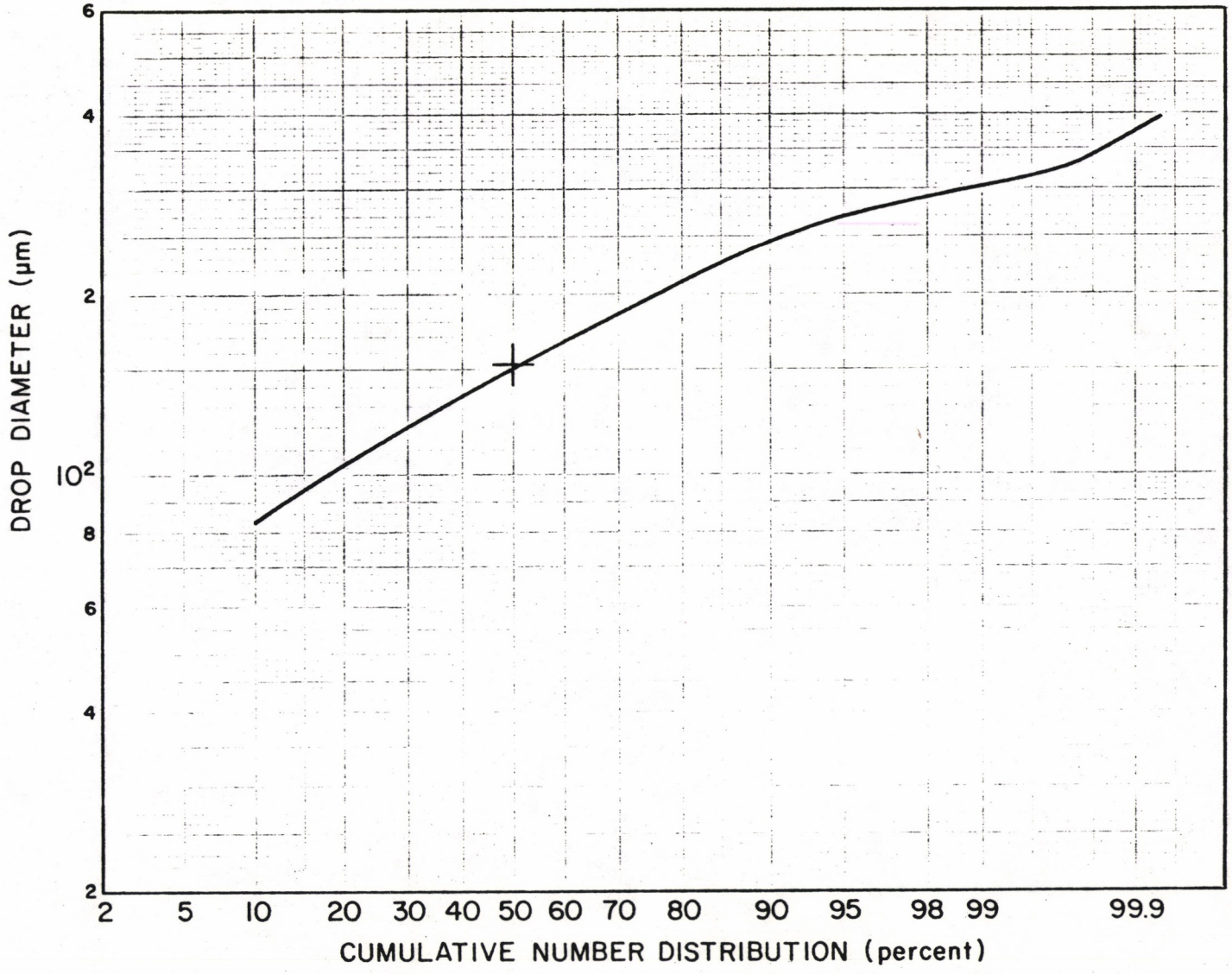


FIGURE 3-7. Cumulative number distribution for Trial 6

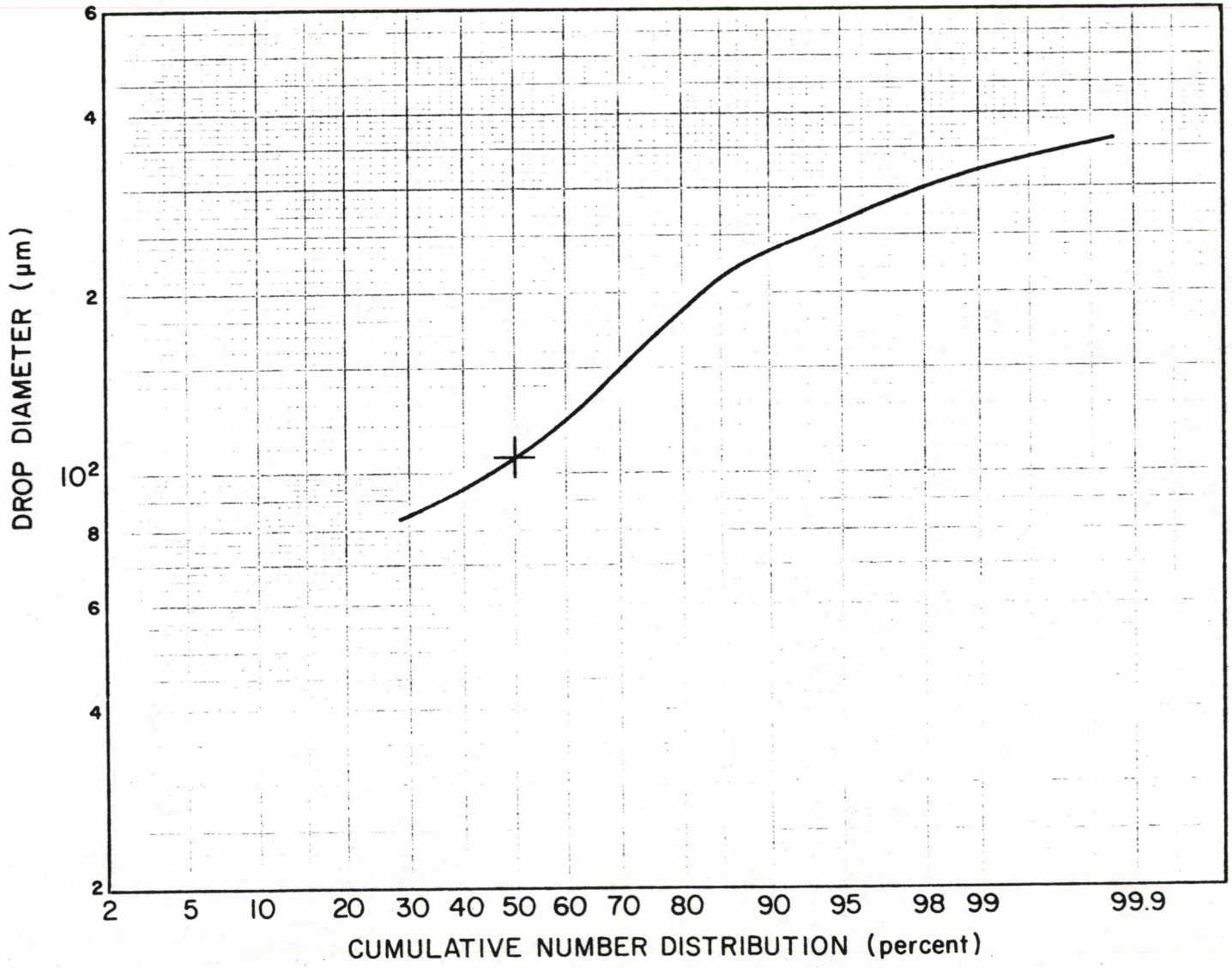


FIGURE 3-8. Cumulative number distribution for Trial 7.

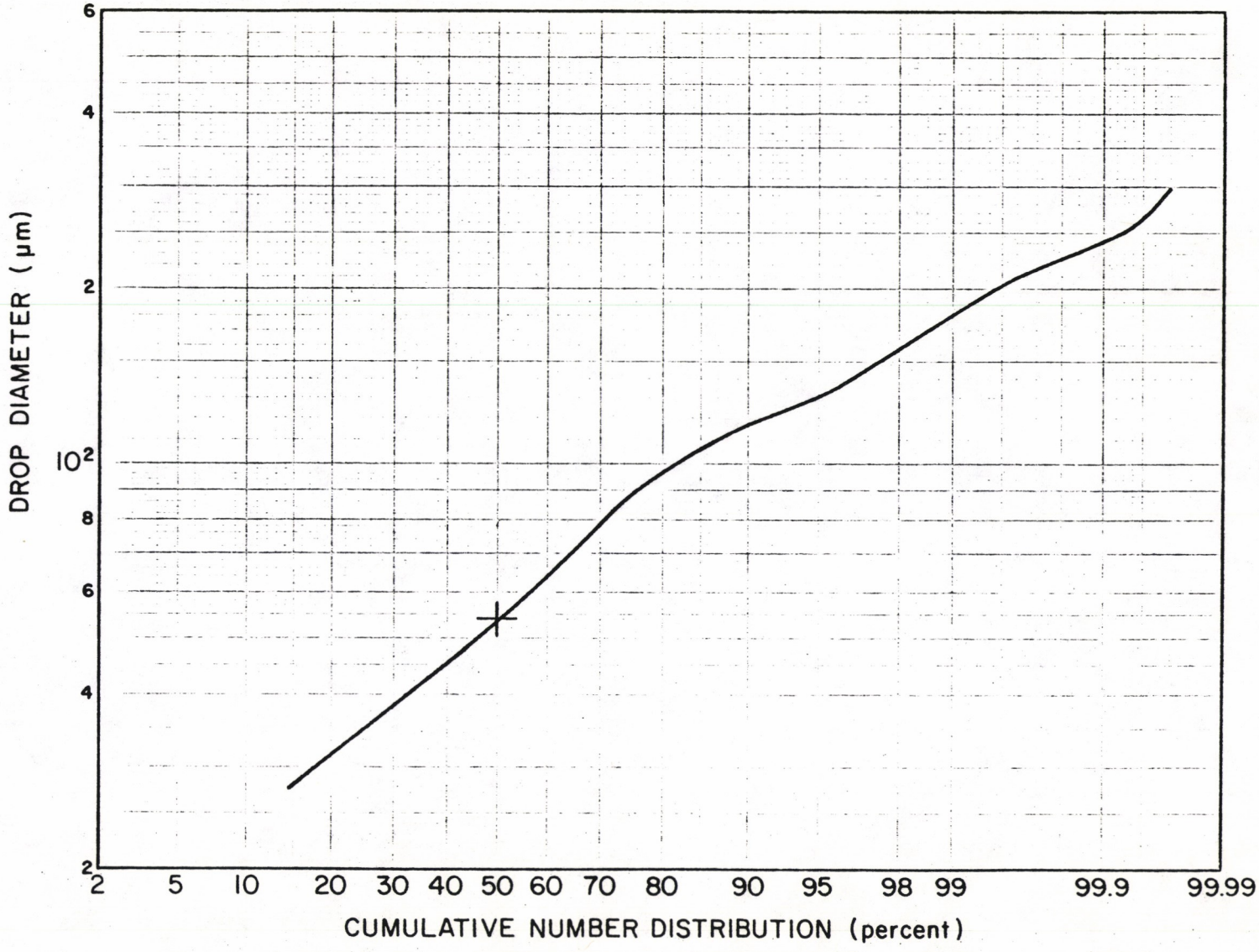


FIGURE 3-9. Cumulative number distribution for Trial 9.

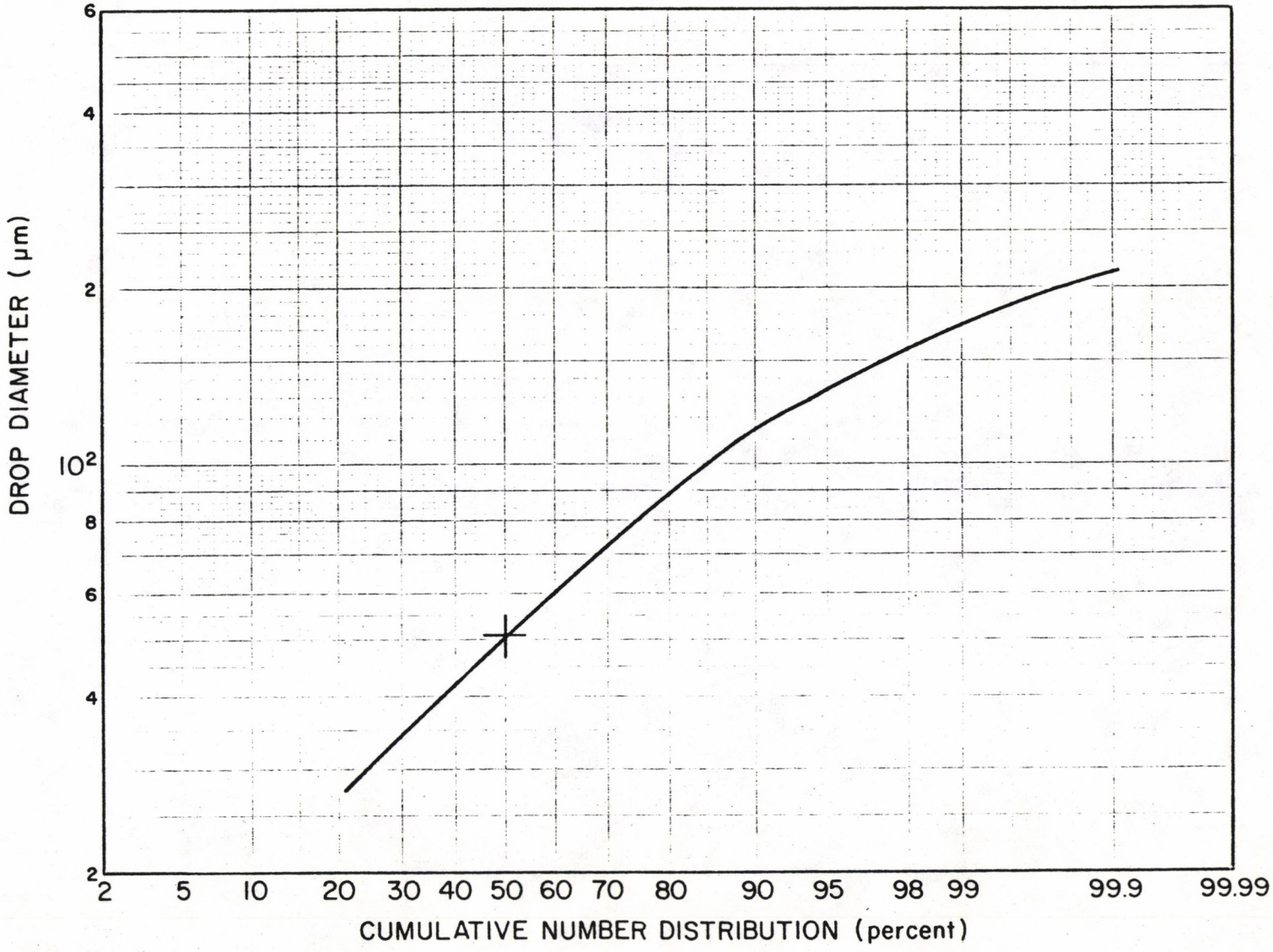


FIGURE 3-10. Cumulative number distribution for Trial 11.

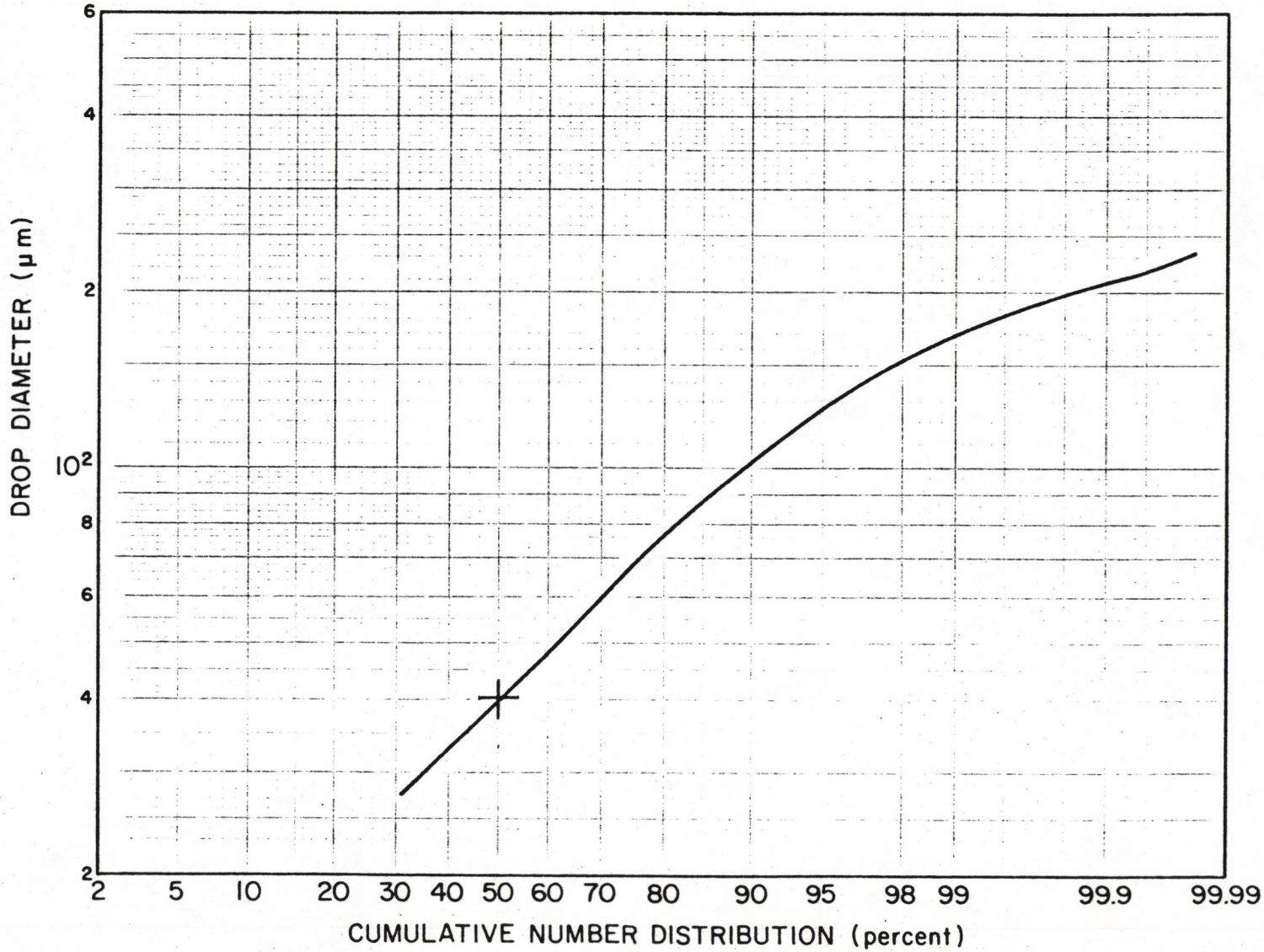


FIGURE 3-11. Cumulative number distribution for Trial 18.

$$= \left( \frac{\pi \rho}{6 (d_{2,i} - d_{1,i})} \right) \left( \frac{d_{2,i}^4 - d_{1,i}^4}{4} \right) \qquad (3\text{-}5)$$

$\rho$ = density of the spray material

$d_{1,i}$ = drop diameter representing the lower limit of the $i^{th}$ size category

$d_{2,i}$ = drop diameter representing the upper limit of the $i^{th}$ size category

The results obtained by applying Equation (3-3) to the drop counts and drop-size data for the five trials are shown in Table 3-4. The mass distributions for Trials 6, 7, 9, 11 and 18 have been plotted on log-probability scales in Figures 3-12 through 3-16.

The mass median diameter is the drop diameter that divides the spray distribution within the swath into two equal parts by mass. The value of the mass median diameter for each trial can be determined from Figures 3-12 through 3-16 by noting the drop diameter corresponding to the 50-percent point of the cumulative distribution and is marked by the symbol + in the figures. Since density is linear with drop size, the mass median diameter and volume median diameter (VMD) are equivalent. The number median diameters (NMD) and volume median diameters (VMD) obtained for the five trials are summarized in Table 3-5.

## 3.3 MASS RECOVERY ESTIMATES

The mass recovered within the swath for each of the five trials was also estimated from the estimates of spray deposit density for each of the sampling cards in the swath. The mass per unit area ($M_j$) deposited on the $j^{th}$ card was estimated from the relationship

## TABLE 3-4

## CUMULATIVE MASS DISTRIBUTIONS FOR TRIALS 6, 7, 9, 11 AND 12

| Trial | Row | | Drop-Size Category (I) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 6 | B | Upper Limit Drop Diameter ($\mu$m) | 83.77 | 128.3 | 171.1 | 212.3 | 251.08 | 289.7 | 325.9 | 360.5 | 393.4 | 424.6 | | |
| | | Cumulative Percent by Mass | .4470 | 5.628 | 23.03 | 45.46 | 67.33 | 89.09 | 97.45 | 98.60 | 99.92 | 100 | | |
| 7 | A | Upper Limit Drop Diameter ($\mu$m) | 83.77 | 128.3 | 171.1 | 212.3 | 251.8 | 289.7 | 360.5 | 424.6 | | | | |
| | | Cumulative Percent by Mass | 1.670 | 11.28 | 22.40 | 36.61 | 58.95 | 79.58 | 98.09 | 100 | | | | |
| 9 | C | Upper Limit Drop Diameter ($\mu$m) | 27.64 | 47.71 | 67.90 | 88.20 | 108.6 | 129.1 | 170.5 | 212.4 | 254.7 | 297.5 | 340.7 | |
| | | Cumulative Percent by Mass | .2032 | 3.276 | 11.18 | 22.00 | 37.34 | 54.72 | 77.92 | 90.73 | 97.27 | 98.61 | 100 | |
| 11 | A | Upper Limit Drop Diameter ($\mu$m) | 27.64 | 47.71 | 67.90 | 88.25 | 108.6 | 129.1 | 149.8 | 170.5 | 191.4 | 212.4 | 233.5 | |
| | | Cumulative Percent by Mass | .2893 | 3.134 | 10.37 | 22.42 | 37.02 | 55.77 | 72.65 | 84.60 | 93.34 | 98.05 | 100 | |
| 12 | B | Upper Limit Drop Diameter ($\mu$m) | 27.64 | 47.71 | 67.90 | 88.25 | 108.6 | 129.1 | 149.8 | 170.5 | 191.4 | 212.4 | 233.5 | 254.7 |
| | | Cumulative Percent by Mass | .5485 | 4.633 | 12.14 | 23.83 | 39.02 | 53.95 | 70.94 | 83.70 | 92.57 | 97.93 | 99.37 | 100 |

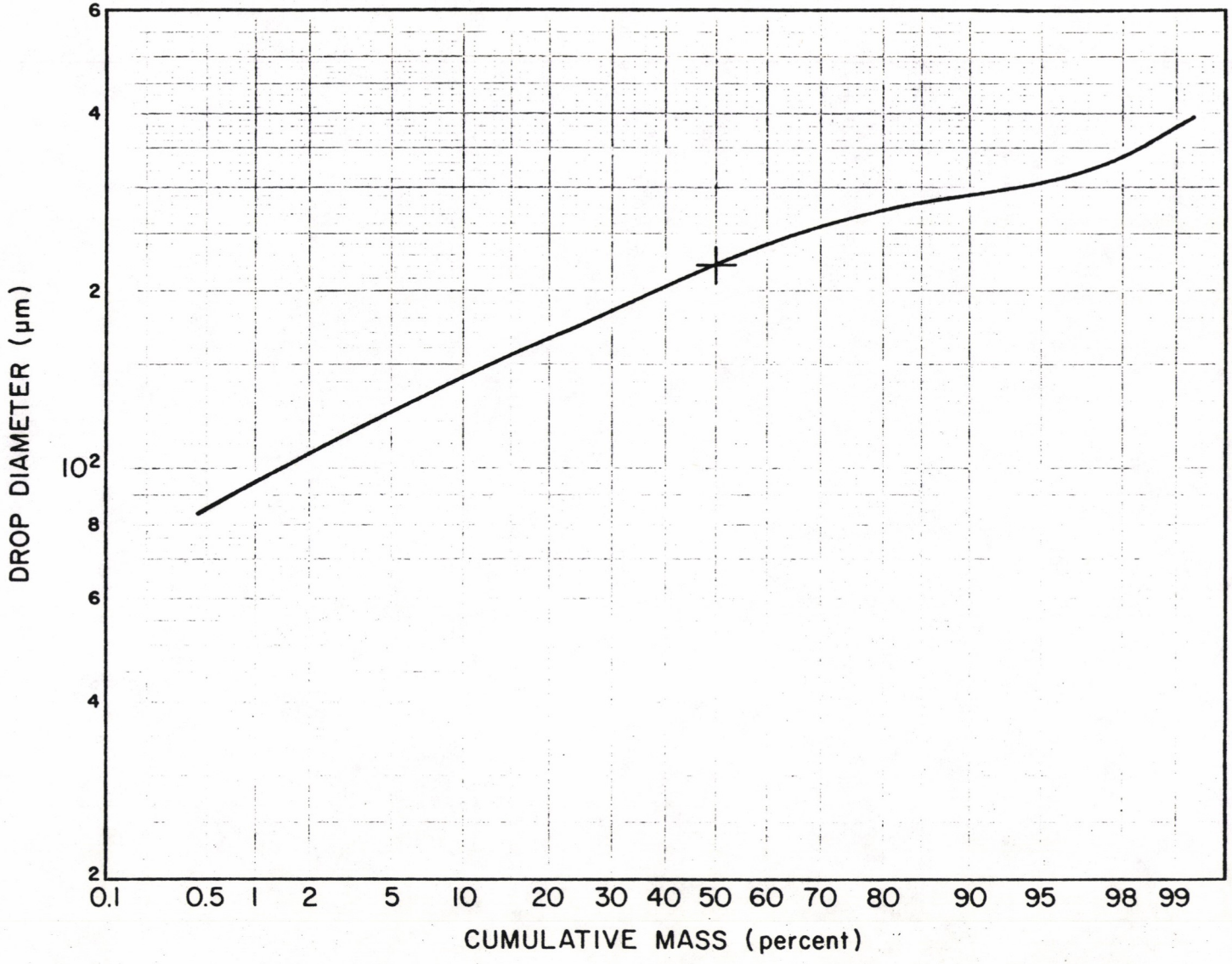


FIGURE 3-12. Cumulative mass distribution for Trial 6.

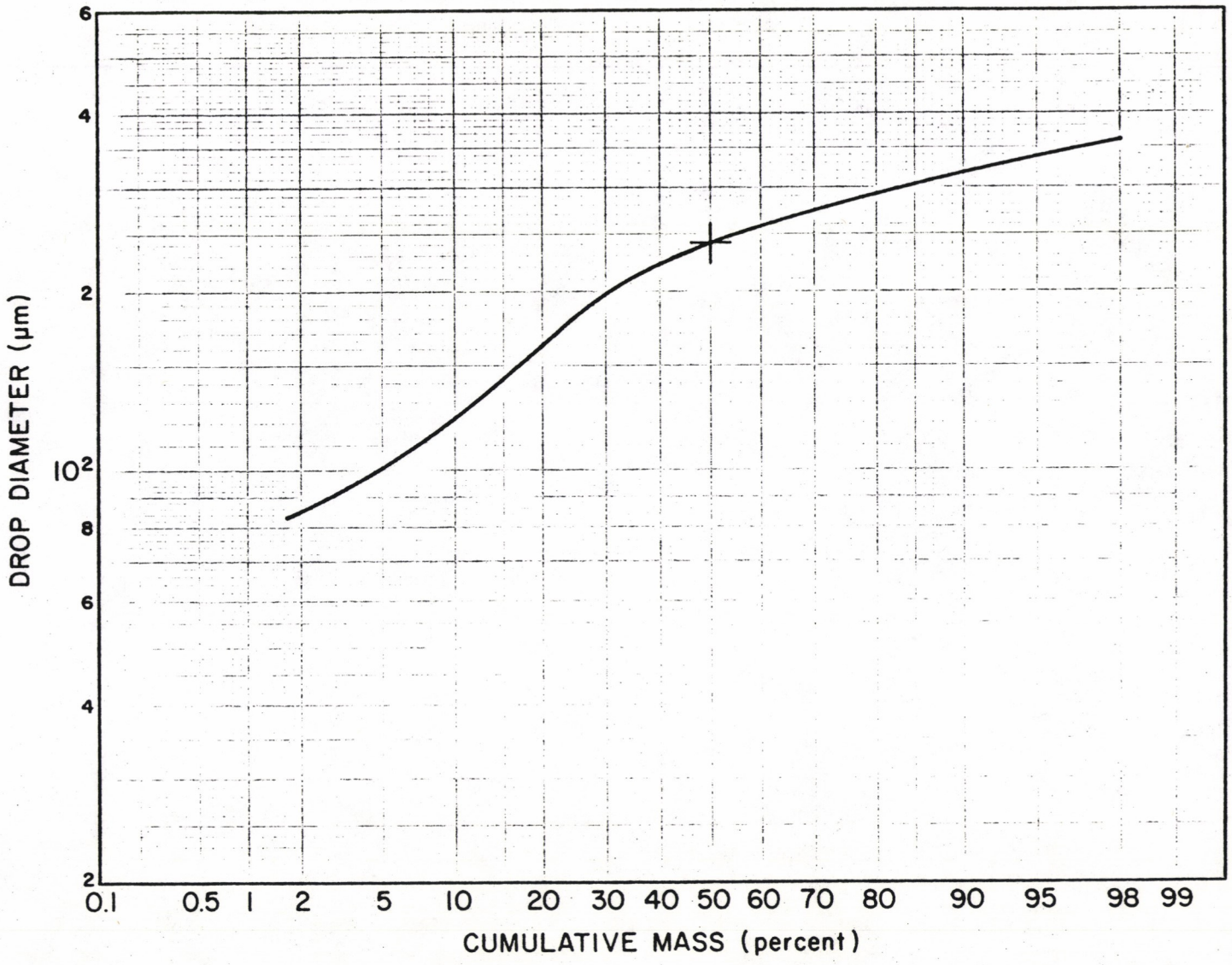


FIGURE 3-13. Cumulative mass distribution for Trial 7.

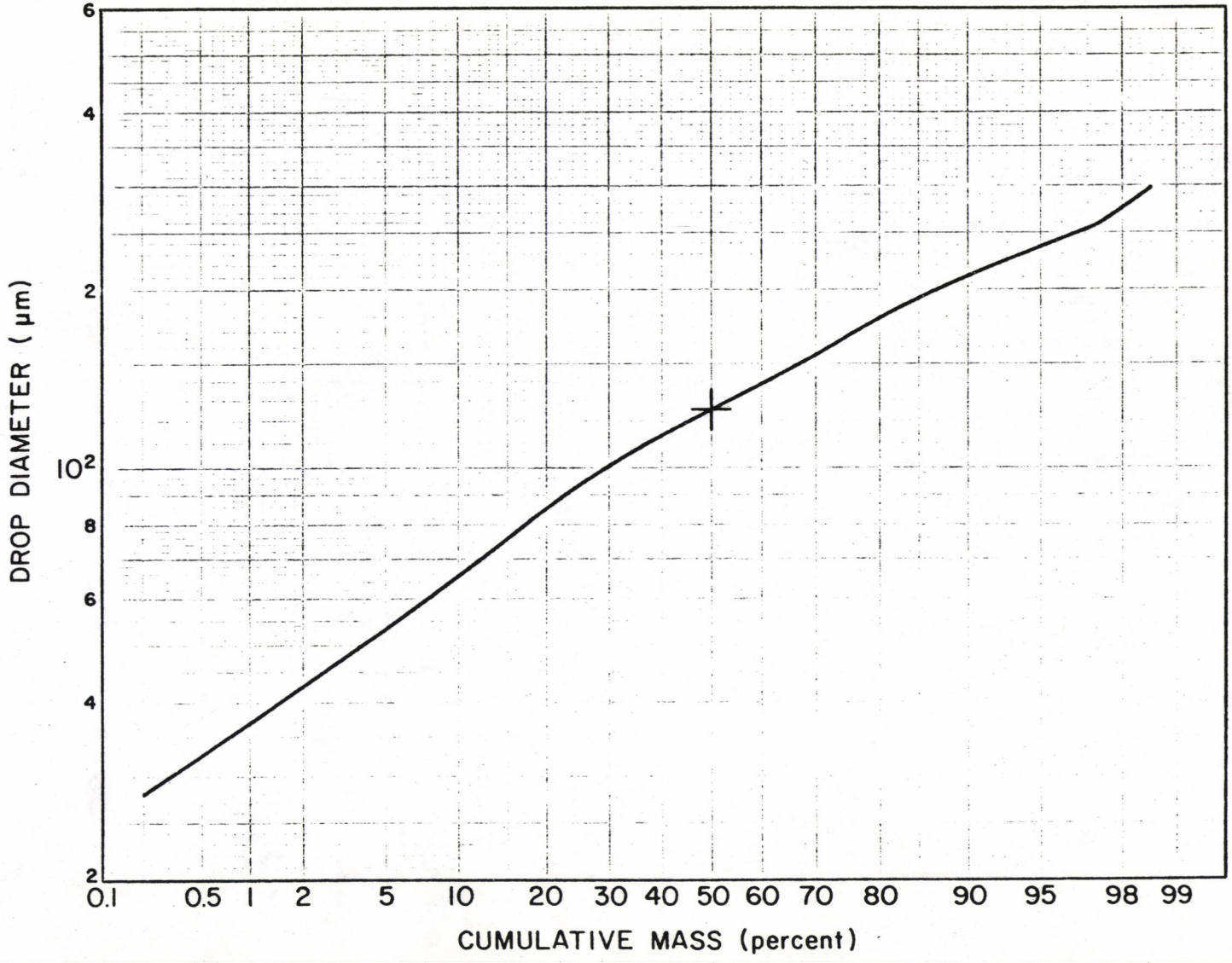


FIGURE 3-14. Cumulative mass distribution for Trial 9.

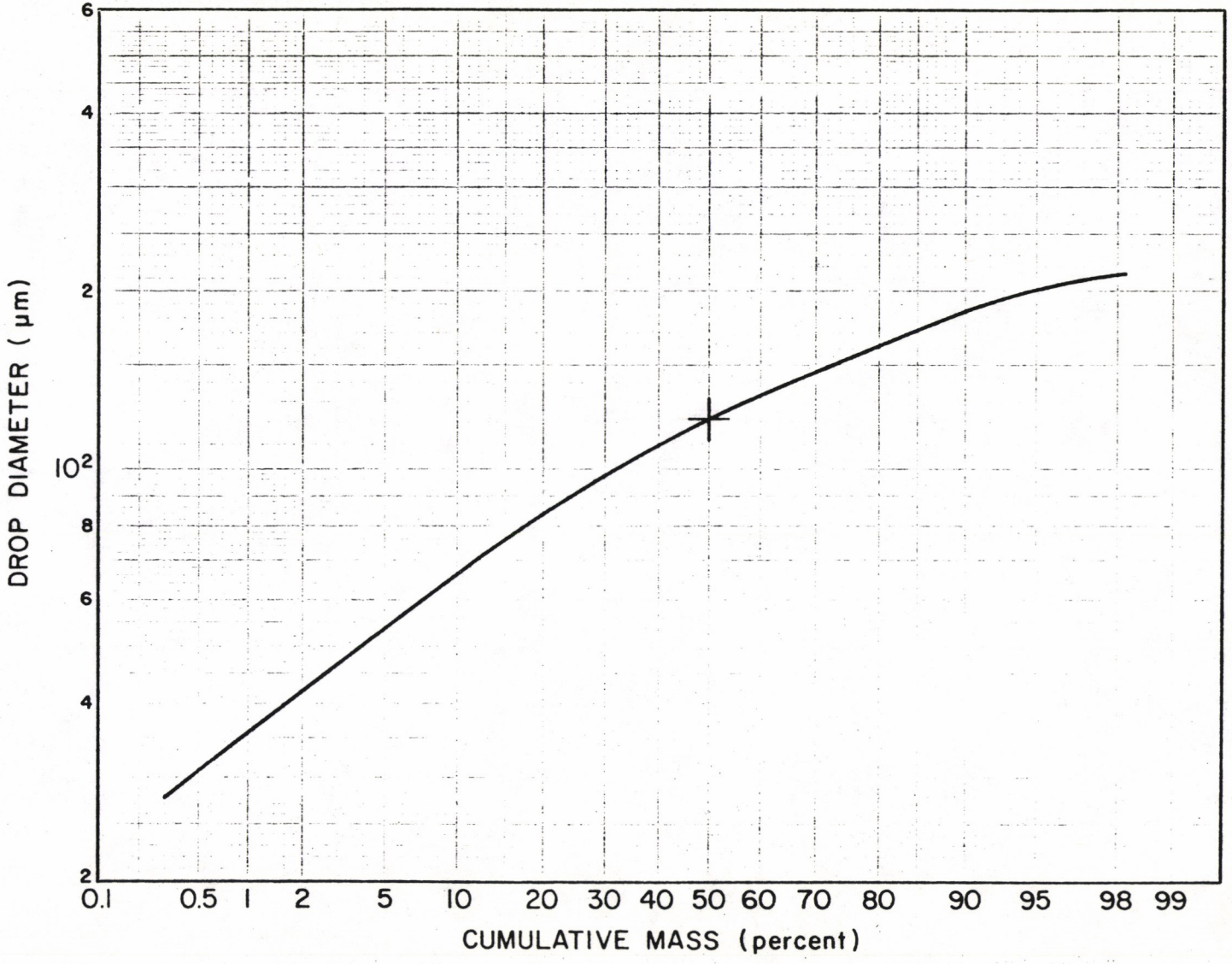


FIGURE 3-15. Cumulative mass distribution for Trial 11.

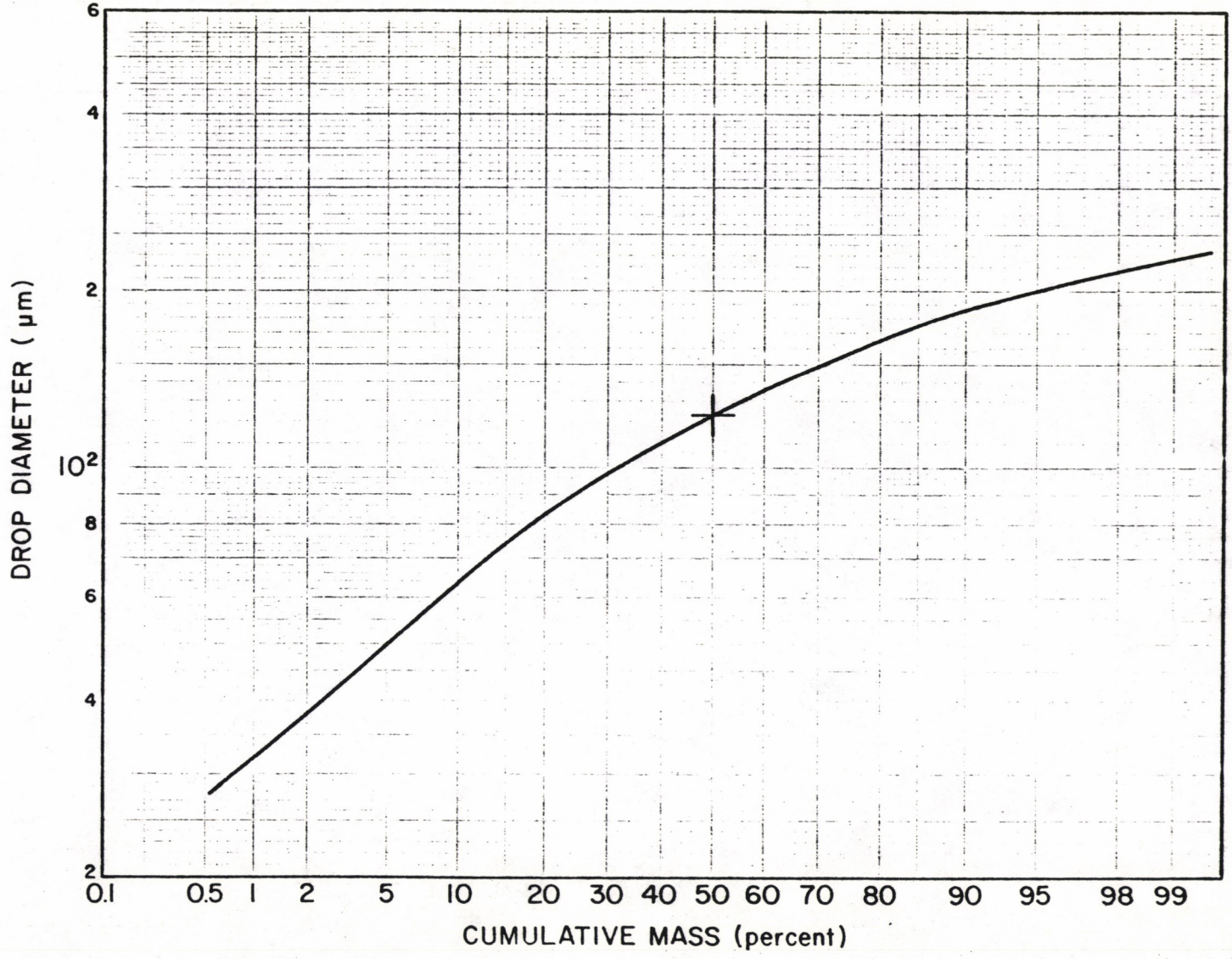


FIGURE 3-16. Cumulative mass distribution for Trial 18.

TABLE 3-5

NUMBER MEDIAN AND VOLUME MEDIAN
DIAMETERS IN MICROMETERS

| | Trial Number | | | | |
|---|---|---|---|---|---|
| | 6 | 7 | 9 | 11 | 18 |
| Number Median Diameter ($\mu$m) | 152 | 106 | 54 | 51 | 40 |
| Volume Median Diameter ($\mu$m) | 220 | 241 | 125 | 121 | 124 |

$$M_j = \frac{1}{A_j} \sum_{i=1}^{I} \overline{m}_i \, n_{i,j} \qquad (3\text{-}6)$$

where the terms appearing in Equation (3-6) have been defined in Section 2 above. The distribution of mass deposition along the sampling lines for Trials 6, 7, 9, 11 and 18 obtained from Equation (3-6) is shown in Figures 3-17 through 3-21. The total mass recovery per unit length of flight path is estimated from the expression

$$MR = S \sum_{j=c}^{d} M_j \qquad (3\text{-}7)$$

where

S = separation distance between cards on the sampling line

Values of the mass recovered in the swath of the five trials calculated by using Equation (3-7) are given in Table 3-6. Table 3-6 also presents estimates of the deposition efficiency within the swath. This was calculated by dividing the mass recovery by the amount of material released by the aircraft per unit length of the flight path and multiplying the result by 100 to obtain units of percent.

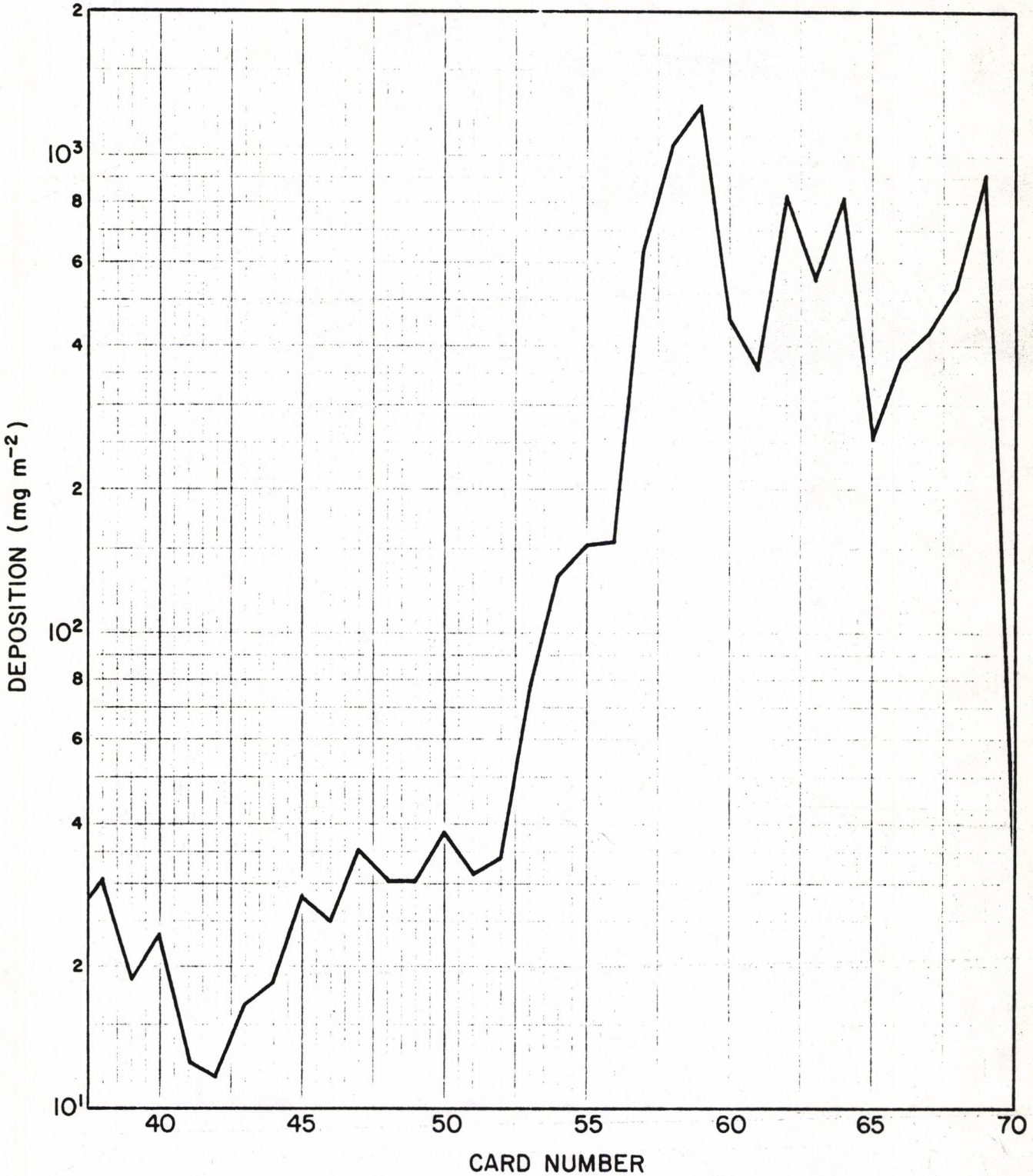


FIGURE 3-17. Mass deposited along the sampling line for Trial 6.

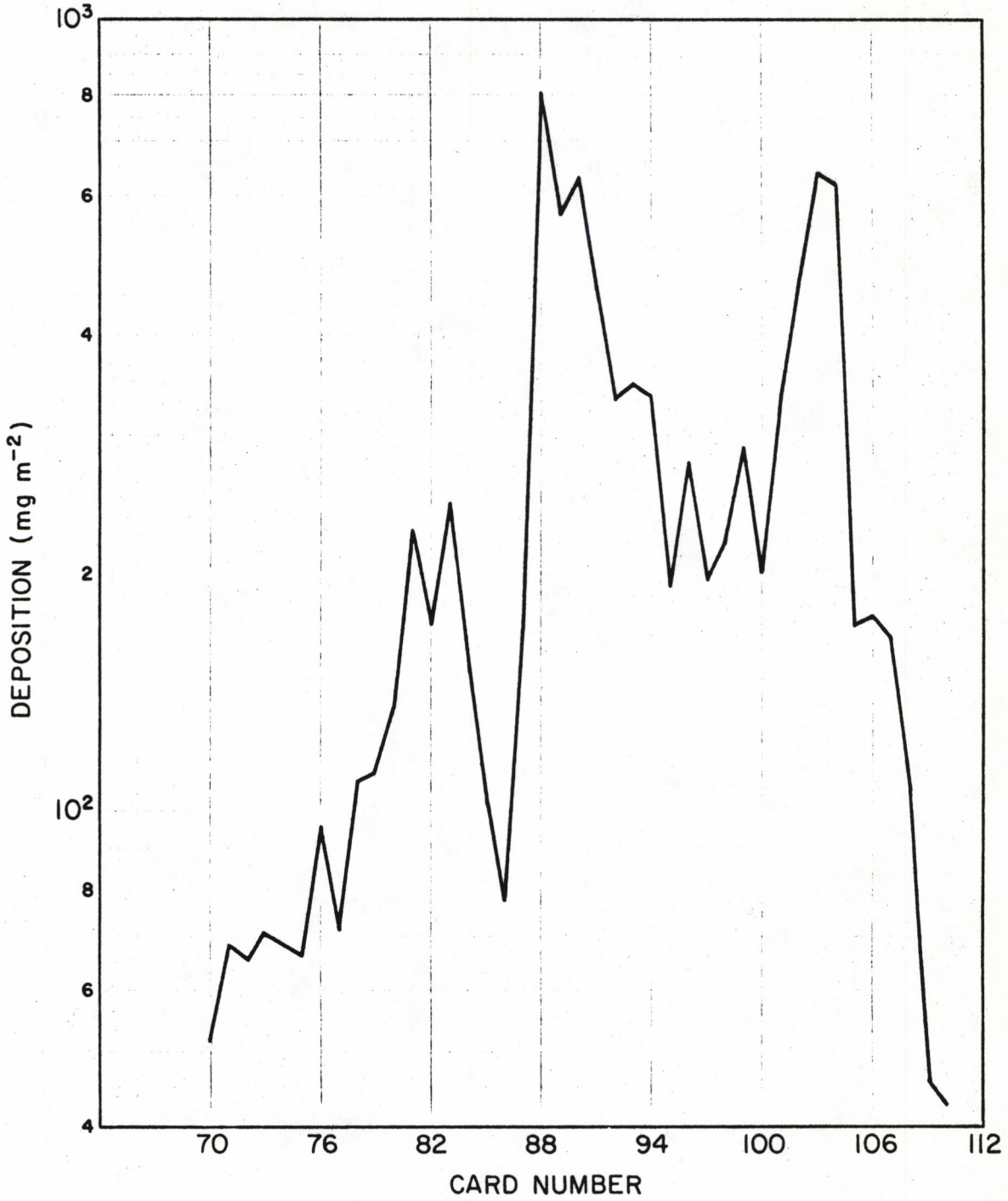


FIGURE 3-18. Mass deposited along the sampling line for Trial 7.

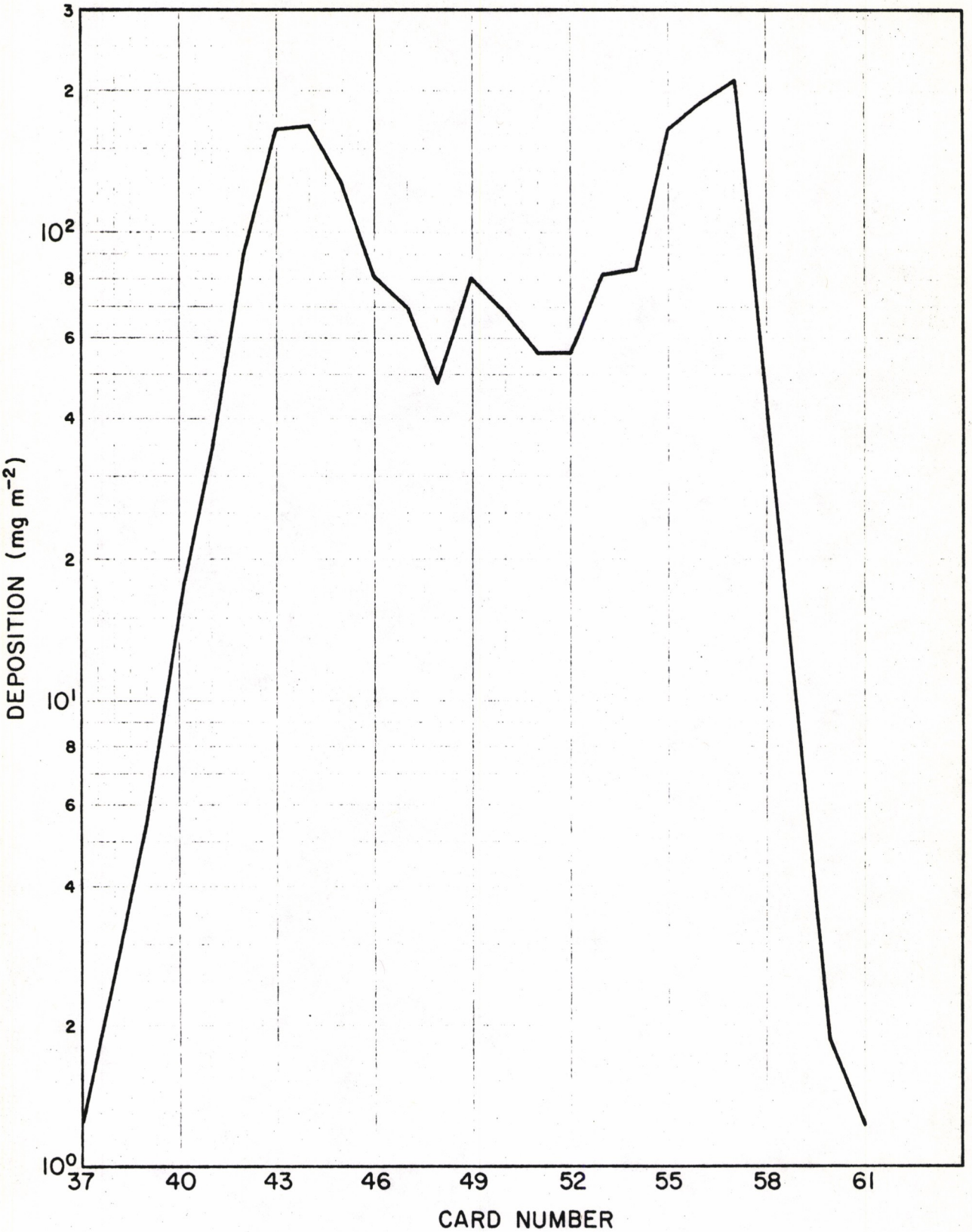


FIGURE 3-19. Mass deposited along the sampling line for Trial 9.

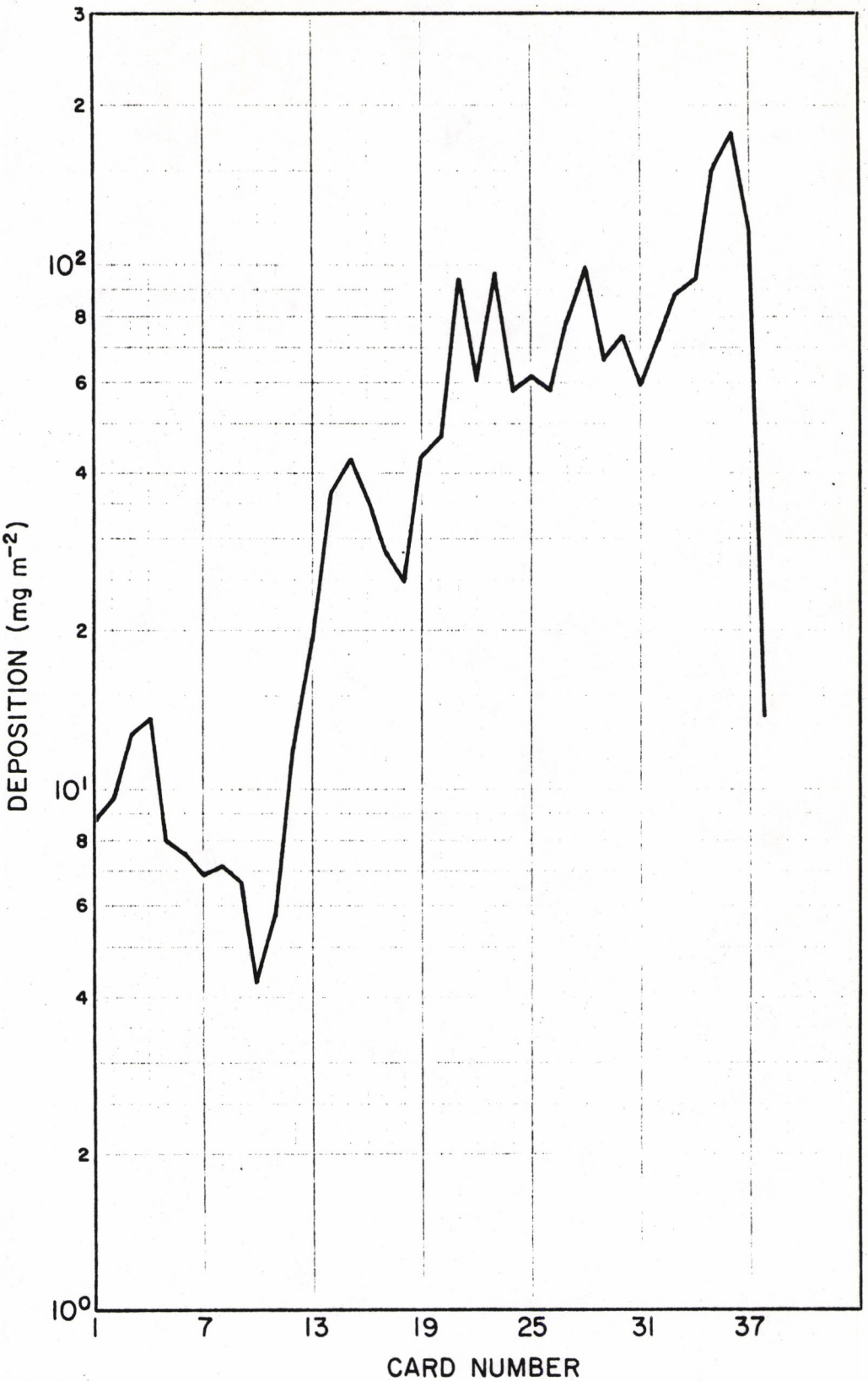


FIGURE 3-20. Mass deposited along the sampling line for Trial 11.

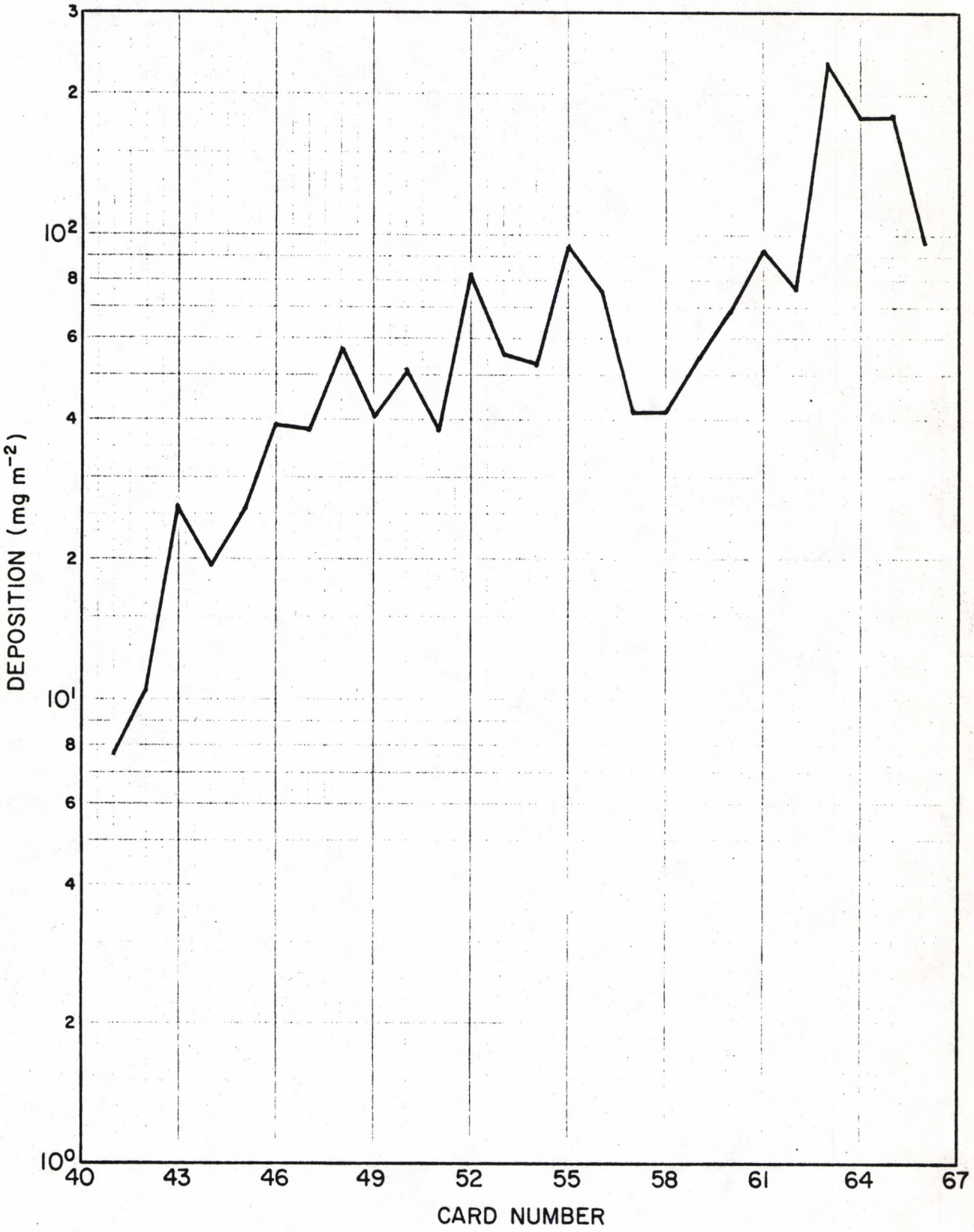


FIGURE 3-21. Mass deposited along the sampling line for Trial 18.

TABLE 3-6

MASS RECOVERY, MATERIAL DISSEMINATED
AND DEPOSITION EFFICIENCY

| | Trial Number | | | | |
|---|---|---|---|---|---|
| | 6 | 7 | 9 | 11 | 18 |
| Mass Recovery ($g\ m^{-1}$) | 17.3 | 26.6 | 5.02 | 4.57 | 4.92 |
| Material Disseminated ($g\ m^{-1}$) | 59.6 | 59.6 | 30.4 | 30.4 | 30.4 |
| Deposition Efficiency (Percent) | 29.0 | 44.63 | 16.5 | 15.0 | 16.2 |

# SECTION 4

# DEVELOPMENT OF A FIELD MANUAL

As noted in Section 1, the major purposes of this study are to establish procedures to achieve reproducible estimates of the deposits on card samplers and to establish methods and procedures for the rapid characterization of aircraft spray. Section 4.1 below describes the procedures followed in developing the recommendations contained in the field manual for designing the sampling grid and for setting meteorological limits. The procedures used in developing the recommendations contained in the field manual for analyzing deposit data to obtain spray characterization information are described in Section 4.2.

## 4.1 DESIGNING THE SAMPLING GRID AND OPERATIONAL CONSIDERATIONS

The decision to recommend inwind aircraft flight patterns rather than crosswind flight patterns for characterizing aircraft spray was reached early in the study. It was evident from the beginning that only a limited number of cards could be analyzed to obtain a rapid quantitative estimate of volume and number median diameters and the mass deposited in an effective swath width. A brief consideration of sampling requirements for crosswind flights relative to those for inwind flights shows that inwind flights are better suited for spray characterization trials. In the absence of atmospheric and aircraft turbulence, a drop with settling velocity $V$ released at a height $H$ above the ground will impact at the distance $x$ downwind from the point of release equal to

$$x = \frac{H\bar{u}}{V} \tag{4-1}$$

where $\bar{u}$ is the mean wind speed in the layer between the ground and height H. For a release height of 50 feet (15.24 meters), a wind speed of 5 miles per hour (2.24 meters per second), a 20-micrometer drop with a settling velocity of 0.0394 feet per second (.012 meters per second) will impact at a distance of about 1.8 miles (2838 meters) from the point of release. A 200-micrometer drop with a settling velocity of 2.3 feet per second (0.7 meters per second) released under the same conditions will impact at about 160 feet from the release point. The presence of atmospheric and aircraft-induced turbulence or downdrafts will cause some of the 20- and 200-micrometer drops contained in a spray cloud to impact at distances closer to the point of release. Nevertheless, sampling lines must extend for relatively long downwind distances to ensure that the full drop spectrum is sampled if the material is released from an aircraft traveling crosswind. With inwind flights, the 20- and 200-micrometer drops travel the same distances, but when the aircraft crosses the sampling line and continues upwind from sufficient distances, drops of all sizes are transported by the wind to the sampling line. The sampling line for inwind releases need only be long enough to contain the effective minimum swath width so that mass per unit area, mass recovery and minimum swath width can be specified. As shown below, the crosswind extent of the sampling lines required for these purposes is relatively small.

The requisite lengths of the aircraft release line upwind of the sampling line and the sampling line itself can be estimated using dispersion-deposition modeling techniques. Ground-level deposition downwind from an instantaneous elevated point source can be expressed by the following relationship (Cramer, et al., 1972)

$$\text{Dep} = \frac{QH}{2\pi \sigma'_A \sigma'_E x^3} \left\{ \exp\left[ -\frac{1}{2}\left( \frac{H - Vx/\bar{u}}{\sigma'_E x} \right)^2 \right] \right\} \left\{ \exp\left[ -\frac{1}{2}\left( \frac{y}{\sigma'_A x} \right)^2 \right] \right\} \qquad (4\text{-}2)$$

where

$Q$ = source strength

$H$ = release height

$\sigma'_A$ = standard deviation of the wind azimuth angle in radians

$\sigma'_E$ = standard deviation of the wind elevation angle in radians

$x$ = downwind distance from the source

$V$ = settling velocity of a drop

$\bar{u}$ = mean wind speed

$y$ = lateral distance from the cloud centerline

The cloud growth in the lateral and vertical is assumed rectilinear with distance from the source. The deposition at a point due to that portion of an inwind line source extending a distance (RL) upwind of the point can be obtained by integrating Equation (4-2) from $x=0$ to $x=RL$. Thus,

$$Dep' = \int_0^{RL} Dep \; dx \tag{4-3}$$

Under the assumption that $\sigma'_A = \sigma'_E$, the above expression becomes

$$Dep' = \frac{Q'H}{2\pi\left(H^2+y^2\right)} \left\{ \frac{\sqrt{2\pi}\,HV}{2\sigma'_E \bar{u}\left(H^2+y^2\right)^{1/2}} \left\{ \exp\left[ \frac{V^2}{2\sigma'^2_E \bar{u}^2} \left( \frac{H^2}{H^2+y^2} - 1 \right) \right] \right\} \right. \tag{4-4}$$

(Equation (4-4) continued on following page.)

(Equation (4-4) continued.)

$$\left\{1 - \operatorname{erf}\left[\frac{\left(H^2+y^2\right)^{1/2}}{\sigma'_E(RL)} - \frac{HV}{\sigma'_E \bar{u}\left(H^2+y^2\right)^{1/2}}\right]\right\}$$

$$+ \left\{\exp\left[\frac{V^2}{2\sigma'^2_E \bar{u}^2}\left(\frac{H^2}{H^2+y^2} - 1\right)\right]\right\} \qquad (4\text{-}4)$$

$$\left\{\exp\left[-\frac{H^2+y^2}{2\sigma'^2_E}\left(\frac{1}{(RL)} - \frac{HV}{\bar{u}\left(H^2+y^2\right)}\right)^2\right]\right\}\Bigg\}$$

where the source strength $Q'$ is expressed as the amount of material released per unit line length. Equation (4-4) can be used to estimate the length of the release line (RL) required to ensure that deposition at the point remains nearly constant as the length (RL) is increased. For example, Figure 4-1 shows deposition at a point for release lines upwind of the point of various lengths using the following inputs in Equation (4-4)

$Q'$ = 1 gram per meter

$\sigma'_E$ = 0.04363 radians (2.5 degrees)

$\bar{u}$ = 4 meters per second

$H$ = 30 meters

$y$ = 0 meters

$V$ = 0.028, 0.08, 0.23, 0.48 meters per second

where the settling velocities $V$ are for spherical drops of unit density corresponding to approximate diameters of 30, 50, 90 and 150 micrometers.

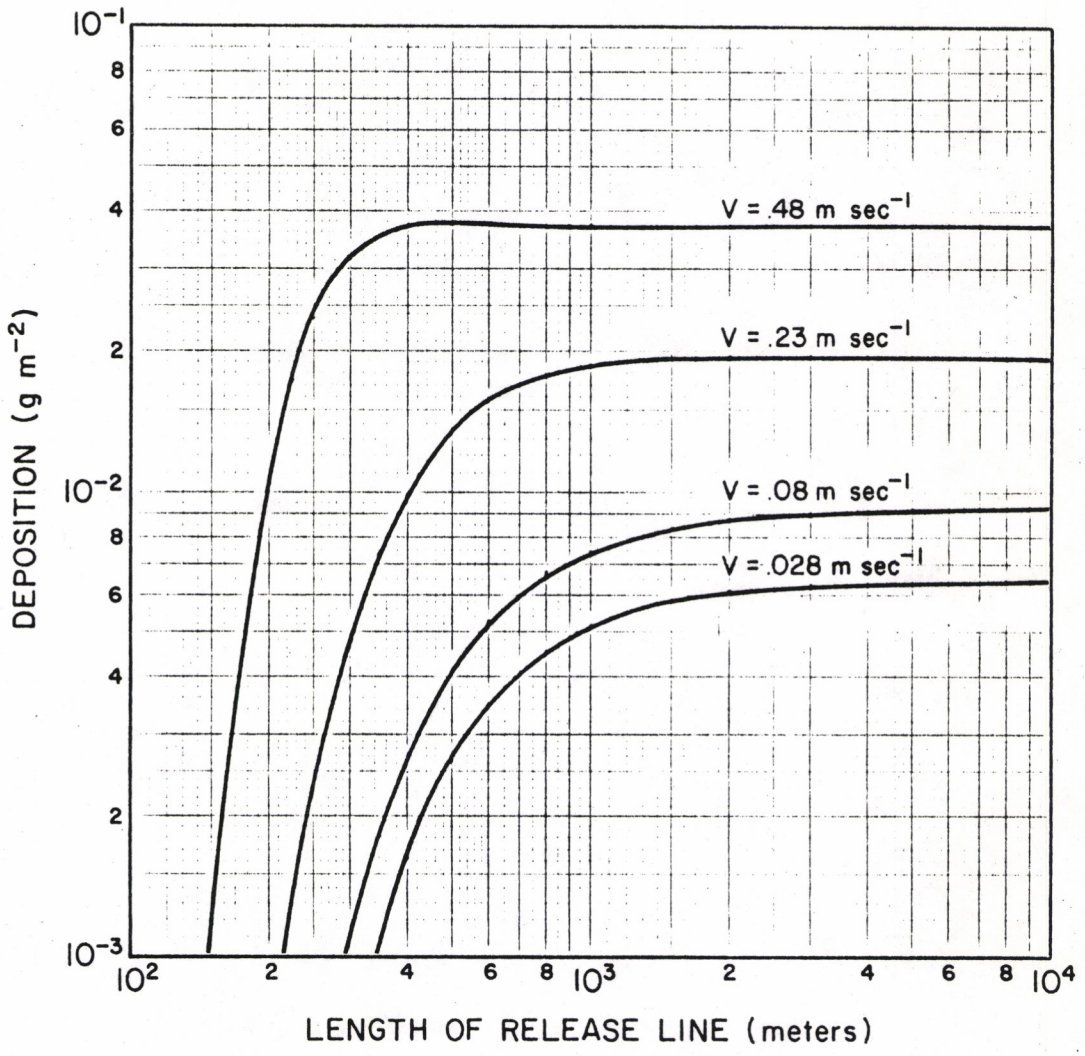


FIGURE 4-1. Ground-level deposition as a function of the upwind length of the release line.

Inspection of Figure 4-1 shows that, for a 30-micrometer drop (V = 0.028 meters per second), the deposition at the point does not increase appreciably after the release line length is about 100 H (3000 meters) or longer. On the other hand, deposition does not increase for a 150-micrometer drop (V = .48 meters per second) after the inwind release line length is about 400 meters or more upwind of the point. Similar curves were plotted for other release heights and for meteorological input parameters expected during characterization trials. Based on an analysis of these data and the experience gained during the Townsend trials, the following general guidelines were developed for use in the field manual:

- If most of the spray cloud mass is contained in drops with diameters 50 micrometers or less and wind speeds $\bar{u}$ are 4 meters per second or less, the length of the release line RL upwind of the sampling grid should be about 100 times the aircraft altitude H (RL = 100H).

- If most of the spray cloud mass is contained in drops with diameters between 50 and 100 micrometers and $\bar{u}$ is equal to or less than 4 meters per second, RL should be about 70 H.

- If most of the spray cloud mass is contained in drops with diameters greater than 100 micrometers and $\bar{u}$ is equal to or less than 4 meters per second, RL should be equal to 35 H.

It should be mentioned that the above estimates of the length of the release line are conservative in the sense that shorter line lengths upwind of the sampling grids might be satisfactory. Aircraft-induced turbulence and wake effects and the fact that the aircraft-generated spray cloud has an initial vertical dimension of at least several meters all act to decrease the required length of the upwind release line.

Equation (4-4) can also be used to estimate the length L of the crosswind sampling line required to contain the swath. Figure 4-2 is a plot of the crosswind deposition profile at the sampling line for an inwind release line length of 3000 meters (100 H), a settling velocity of 0.028 meters per second, an aircraft altitude of 30 meters, source strength of 1 gram per meter, and values of $\sigma_E$ equal to 2.5 and 5 degrees. The abcissa is labeled in units of nH, where y in Equation (4-4) has been set to nH. Inspection of Figure 4-2 shows that deposition at a crosswind distance of $\pm$ 3H ($\pm$ 90 meters) is nearly a factor of 10 less than at the center of the swath. Thus, a crosswind sampling line length equal to 6H would ensure that about 90 percent by mass of deposition from a spray cloud comprised of 30-micrometer drops would be contained within the sampling line. The deposition for drops of large diameter decreases more rapidly in the lateral or crosswind direction. For this reason, more than 90 percent by mass of deposition from clouds comprised of drops 30 micrometers and greater would be contained within a swath width of 6H. A crosswind line length L equal to 10 H is recommended for use in the field manual to allow for some error in the aircraft crossing the sampling grid at the center of the sampling line.

From 10 to 20 samplers should be in the swath to adequately define the crosswind deposition profile. If, for example, we require that 15 samplers be within the crosswind sampling length 6 H, then the requisite sampler spacing S is

$$S = \frac{6\,H}{15} = 0.4\,H \qquad (4\text{-}5)$$

Since the recommended length of the sampling line L is 10 H, a total of 25 samplers should be used on each sampling line. The trials at Townsend indicated that a sampler spacing of 0.4 H is more than adequate; a value of S = 0.4 H is therefore recommended in the field manual. Thus, for an aircraft release height of 30 meters, the

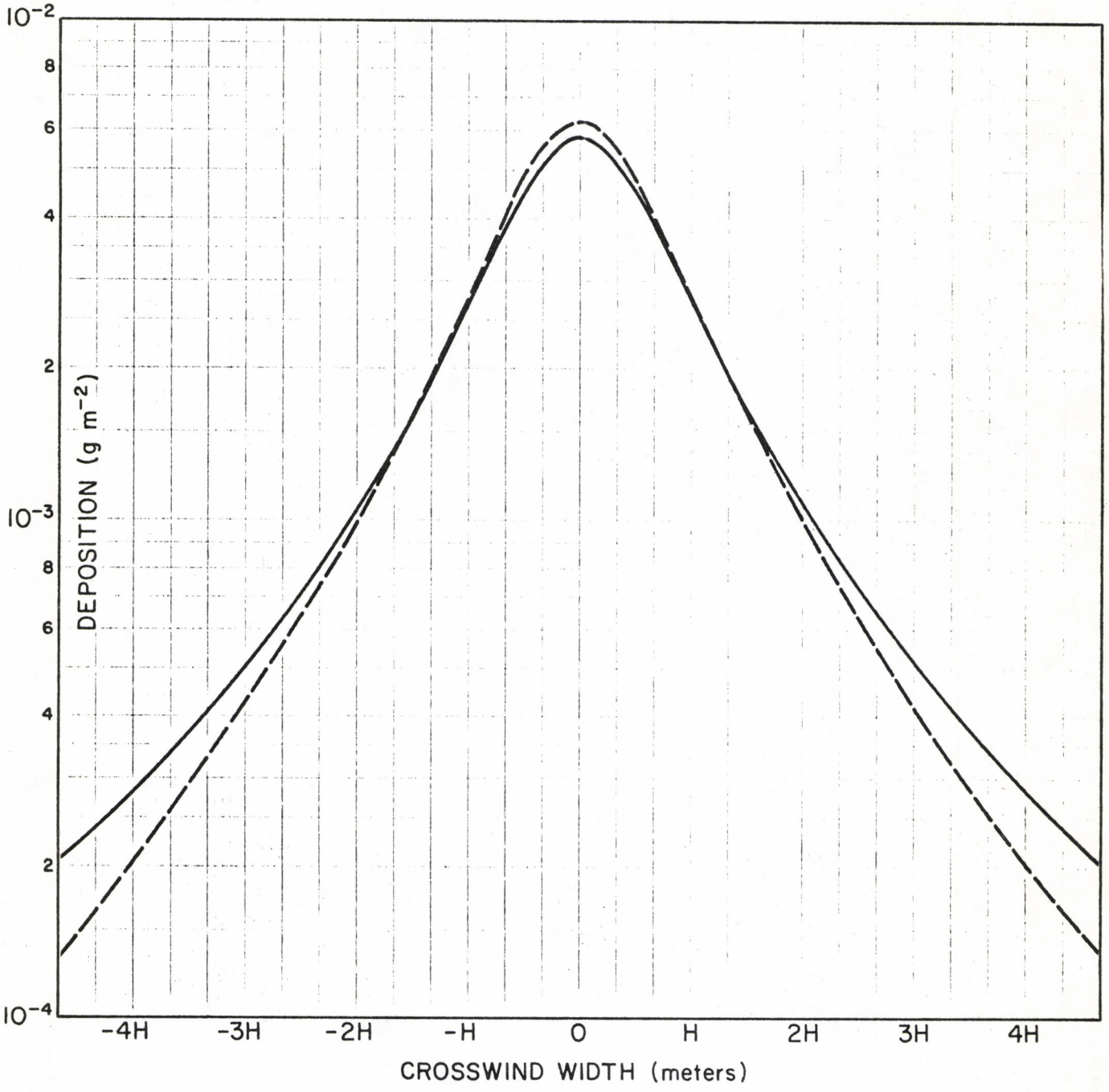


FIGURE 4-2. Crosswind deposition for an upwind release line length of 100 H, H = 30 meters and V = 0.028 meters per second. The dashed line is for $\sigma_E = 2.5$ degrees and the solid line is for $\sigma_E = 5$ degrees.

recommended sampling line length is 300 meters with a sampler spacing of 12 meters along the line.

Inspection of Figure 2-1 shows that the sampling lines on the Townsend trials were approximately in the shape of an equilateral triangle. While it was not recognized at the time, a grid design in the shape of an equilateral triangle is ideally suited for spray characterization trials, since this design can accommodate large variations in wind directions without introducing large errors in the analysis of sampler card data. Figure 4-3 is a diagram of the sampling design recommended in the field manual. Inspection of Figure 4-3 shows that this design tends to limit the angle between the aircraft flight path (flown into the wind) and a sampling line to 90 ± 30 degrees. An example of the flexibility of the grid design for use with various wind directions is shown in Figure 4-4. If north is assumed toward the top of Figure 4-4, sampling line A in Figure 4-4 can be used for all winds from 150 through 210 degrees and from 330 through 30 degrees. Sampling line B in Figure 4-4 can be used for all winds from 30 through 90 degrees and from 210 through 270 degrees; similarly, sampling line C in Figure 4-4 can be used for all winds from 90 through 150 degrees and from 270 degrees through 330 degrees. The choice of the proper flight path for any given trial depends on the mean wind direction measurements made just prior to conduct of the trial.

High wind speeds and high levels of ambient atmospheric turbulence are not conditions recommended for conducting spray characterization trials for several reasons. First, high winds and turbulence levels require the inwind release line be extended to much longer upwind distances from the sampling lines and also require longer sampling lines. Second, the consequent enhanced downwind spray drift results in decreased deposition in the swath and possibly may cause the spotting of cars and other objects outside the sampling grid area. For these reasons, the recommendation is made in the field manual to conduct spray characterization trials when mean wind speeds are less than 4 meters per second (9 miles per hour)

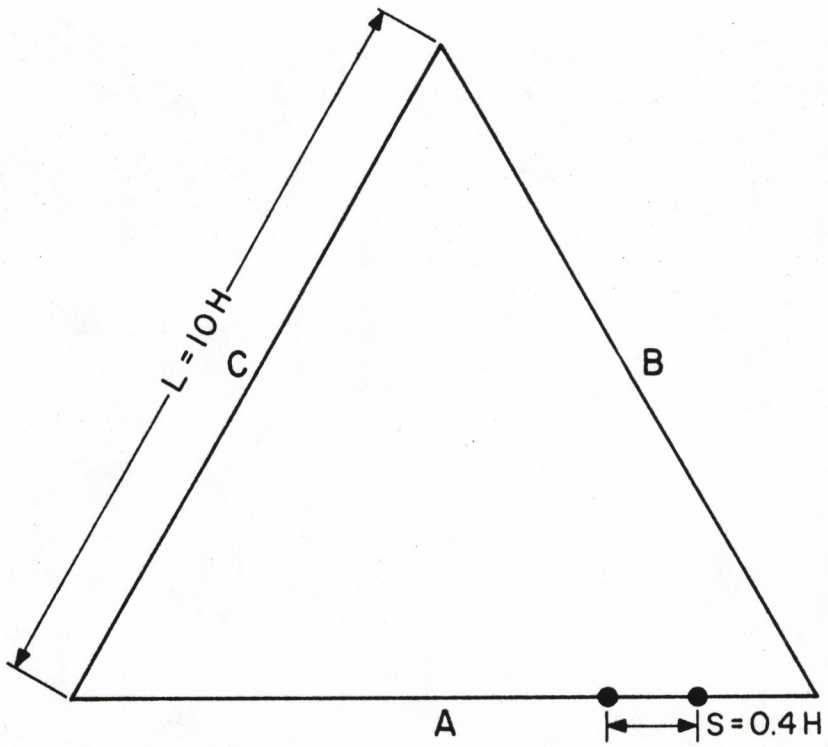


FIGURE 4-3. Simple equilateral triangle sampling grid for characterizing aircraft spray. The length of the sides L are 10 times the aircraft flight altitude H and the sampler spacing S is 0.4H.

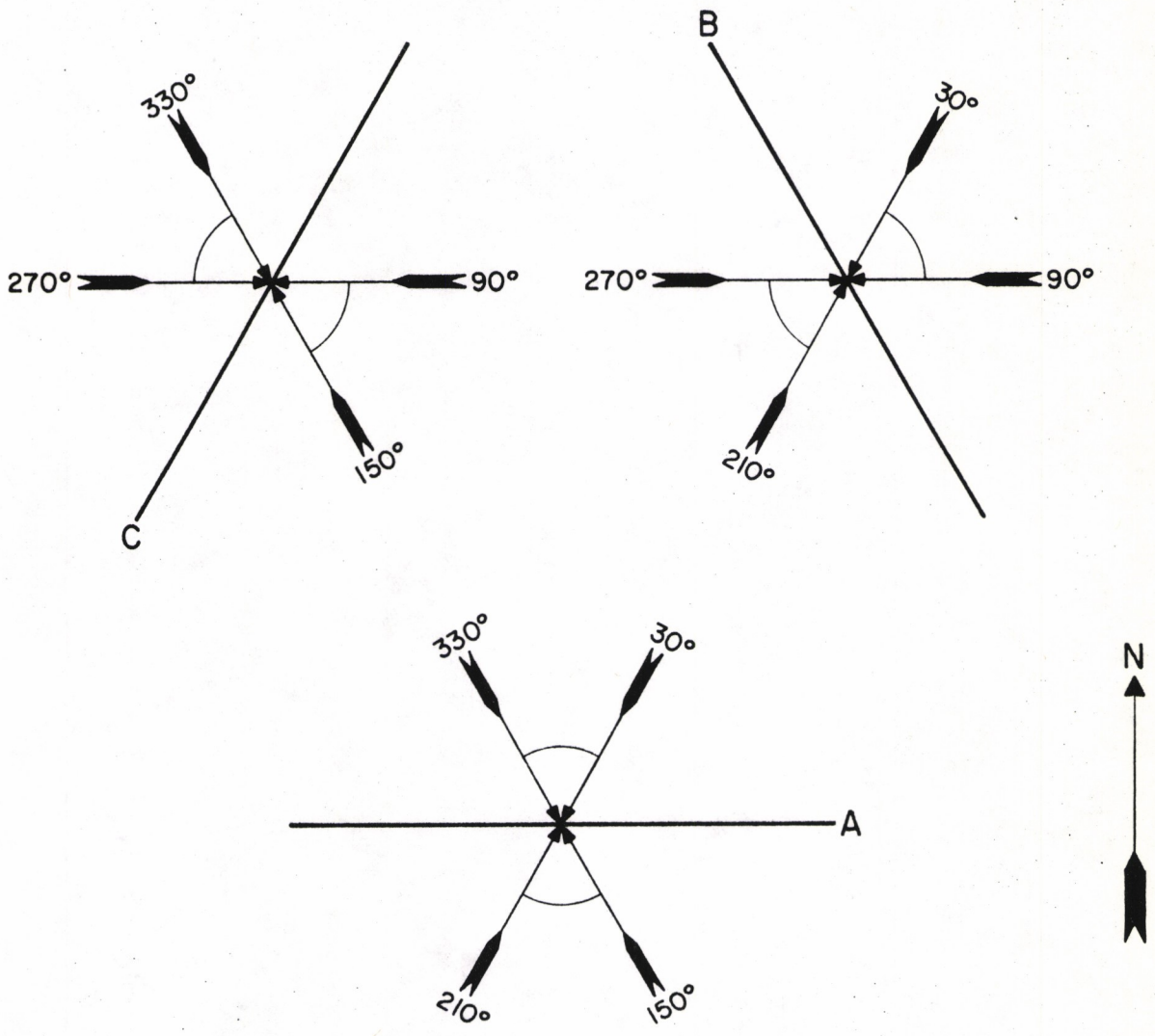


FIGURE 4-4. Illustration of the use of the sampling lines of the grid design shown in Figure 4-3 with winds from various directions.

and when ambient turbulence levels are moderate or low. Section 3.2.3 of the field manual is reproduced in Appendix A and contains a description of a visual method, using smoke from smoke grenades, for judging ambient turbulence levels. Section 3.2.3 of Appendix A also contains procedures for determining the sampling line for use in the trial from wind direction measurements.

## 4.2 ANALYSIS OF SAMPLING CARD DATA

The second major purpose of this study was to establish methods and procedures and to recommend equipment to enable two or three persons to obtain quantitative estimates of spray deposit density, volume median diameter, number median diameter, mass deposition and the minimum effective swath width from the sampling data within 5 hours after flight time. The basis of the recommendations for accomplishing these objectives made in the field manual is discussed in the following paragraphs.

### Spray Deposit Density

The density of drops deposited on the sampling cards can only be quantitatively estimated by counting the stains, using a suitable magnifying instrument and template to mark the area to be counted. As noted in Section 3.1, difficulty was encountered in obtaining similar and unbiased estimates of spray deposit density using two analysts during the post-trial analysis. Although no definite conclusion could be drawn from the brief study performed, it appeared that the difficulties occurred because different areas of the cards were counted by the analysts and because different estimates of the number of drops with stains less than 50 micrometers in diameter were obtained. For this reason, the Bausch and Lomb No. 81-34-35 measuring magnifier is recommended for use only when drops having stain diameters less than 50 micrometers are not of major interest. Also, the

template for use in the counting procedure was redesigned so that the same area would be counted by the analysts. Since the estimation of spray deposit density by counting stains is usually mastered with only limited experience and proceeds rather rapidly, the field manual contains the recommendation that spray deposit density be estimated by counting a minimum of 200 stains on each of the sampling cards within the swath.

## Volume Median Diameter

Two methods were used for obtaining "quick-look" estimates of the VMD while in the field immediately following a trial: the direct-estimation method suggested by Mr. McIntyre and the D-max method suggested by Maksymiuk (1964). The results obtained from these two procedures are discussed in Section 2.5 and summarized in Table 2-2. In general, the D-max method yielded larger-diameter estimates than the direct-estimation procedure. Table 4-1 shows a comparison of VMD estimates obtained in the field using these two procedures with similar estimates made during the post-trial analysis from the cumulative mass distributions. Table 4-1 indicates that, except for Trials 6 and 7, the D-max method employed during the post-trial analysis yields VMD estimates slightly larger than VMD's obtained from the cumulative mass distribution curves for the trials. On the other hand, the direct-estimation method tends to yield estimates of VMD that are lower than VMD's from the cumulative mass distributions, except for Trial 6. Because the D-max method is considerably easier for untrained personnel to apply, it is recommended in the field manual for estimating VMD's in the field for a "quick-look" analysis immediately after a trial has been conducted.

Prior to the field trials at Townsend, it was hoped that simple transformation formulas, based on the assumption that the drop diameters were log-normally distributed, could be used to obtain average mass and number median diameters from estimates of the volume median diameter made using either the direct-estima-

TABLE 4-1

ESTIMATES OF VOLUME MEDIAN DIAMETERS ($\mu$m) FROM THE FIELD AND POST-TRIAL ANALYSES

| Trial Number | Field Direct-Estimation | D-max Method | | Cumulative Mass Distribution |
|---|---|---|---|---|
| | | Field | Post-Trial | |
| 6 | 223 | 236 | 206 | 220 |
| 7 | 202 | 206 | 200 | 241 |
| 9 | 114 | 155 | 145 | 125 |
| 11 | 101 | 149 | 145 | 121 |
| 18 | 112 | | 145 | 124 |

tion or D-max techniques. The results of the post-trial analysis indicated, however, that such relationships were very sensitive to the geometric standard deviations of the drop distributions and that the geometric standard deviations could not be estimated for different spray materials with sufficient accuracy without measuring the mass or number distribution. For this reason, we believe drop-size distributions of the spray deposit are required. Measurement of the mass distribution should also yield more quantitative estimates of the VMD for a given trial.

Because of the limitation on time and personnel for analyzing the card data, the decision was made to investigate means of reducing the number of cards analyzed and the consequent effect on estimates of VMD. Experience in analyzing the card data during the post-trial period indicated that two relatively inexperienced analysts could count and size drops as well as calculate the mass distribution, using 3 to 5 cards in the swath, within 5 hours after flight time. Table 4-2 shows VMD's estimated from the mass distribution obtained by analyzing 3, 5 and all the cards in the swath. The total number of cards in the swath is also shown in the table. The 3 cards used in the analysis were selected from the center and the two ends of the swath. When 5 cards were used, 2 additional cards located midway between the center card and the ends of the swath were analyzed. As Table 4-2 shows, VMD's estimated by obtaining the mass distributions from 5 cards were very similar to those obtained using all the cards, the maximum error of 5.8 percent occurring in Trial 11.

## Number Median Diameter

Number median diameters estimated from the number distribution from all cards in the swath and from 5 cards in the swath are given in Table 4-3. The data presented in Table 4-3 show that number median diameters obtained from an analysis of 5 cards in the swath are very similar to those obtained by analyzing all cards in the swath.

TABLE 4-2

VOLUME MEDIAN DIAMETERS ESTIMATED FROM THE MASS DISTRIBUTION FROM 3, 5 AND ALL CARDS IN THE SWATH

| Trial Number | Total Number of Cards in Swath | Volume Median Diameters ($\mu$m) | | |
|---|---|---|---|---|
| | | All Cards | 5 Cards | 3 Cards |
| 6 | 8 | 220 | 216 | 210 |
| 7 | 31 | 241 | 252 | 265 |
| 9 | 15 | 125 | 128 | 132 |
| 11 | 17 | 121 | 128 | 135 |
| 18 | 19 | 124 | 121 | 121 |

TABLE 4-3

NUMBER MEDIAN DIAMETERS ESTIMATED FROM THE NUMBER DISTRIBUTION FROM 5 CARDS AND ALL CARDS IN THE SWATH

| Trial Number | Number Median Diameter ($\mu$m) | |
|---|---|---|
| | All Cards | 5 Cards |
| 6 | 152 | 151 |
| 7 | 106 | 115 |
| 9 | 54 | 52 |
| 11 | 51 | 51 |
| 18 | 40 | 39 |

## Average Mass Diameter

Estimates of the average mass diameter (AMD) are used in the recommended field procedure for estimation of mass recovery in the swath. Table 4-4 gives values of the average mass diameters estimated from the mass distribution obtained by analyzing 3, 5 and all cards within the swath.

## Mass Recovery Estimates

Because in many cases all sampling cards within the swath cannot be analyzed for mass deposition, the following procedure is recommended in the field manual for estimating mass recovery in the swath. The mass in milligrams associated with the average mass diameter drop, estimated from the analysis of the mass distribution on 5 cards within the swath, is calculated from the expression

$$\overline{m} = 5.236 \times 10^{-10} \rho (AMD)^3 \qquad (4\text{-}5)$$

where the units of AMD are micrometers and the density of the spray material $\rho$ is in grams per cubic centimeter. The AMD for the swath is assumed representative of the AMD for each card in the swath. The mass per unit area deposited on the $j^{th}$ card in the swath ($M_j$) is then estimated from the expression

$$M_j \text{ (mg cm}^{-2}) = \overline{m} N_j \qquad (4\text{-}6)$$

where

$N_j$ = spray deposit density for the $j^{th}$ card in the swath

TABLE 4-4

AVERAGE MASS DIAMETERS ESTIMATED FROM THE MASS DISTRIBUTION FROM 3, 5 AND ALL CARDS IN THE SWATH

| Trial Number | Average Mass Diameter ($\mu$m) | | |
|---|---|---|---|
| | All Cards | 3 Cards | 5 Cards |
| 6 | 180 | 179 | 172 |
| 7 | 164 | 177 | 186 |
| 9 | 82 | 88 | 95 |
| 11 | 82 | 81 | 86 |
| 18 | 74 | 72 | 75 |

The estimated mass recovered in the swath MR in units of grams per meter is thus

$$MR\,(g\,m^{-1}) = 10\,S \sum_{j=c}^{d} M_j \qquad (4\text{-}7)$$

where S is the sampler separation distance in meters.

Mass recoveries using the above procedure based on the analysis of data from 5 cards are compared with mass recoveries estimated from the mass deposited on all cards within the swath in Table 4-5. The largest estimation error occurs for Trial 7 where the 5-card analysis procedure overestimates the mass recovery estimate from all cards in the swath by 27 percent.

It should be noted that the mass recovery estimates in Table 4-5 are based on the analysis of sampling cards designated as being within the swath, where the swath width was specified, except for Trial 7, as the distance between sampling cards on the sampling line showing spray deposit densities greater than 20 drops per square centimeter. For Trial 7, the flight altitude was 50 feet higher than during the other trials and resulted in a lower spray deposit density over a greater distance along the sampling line. The swath width for Trial 7 was specified as the distance between sampling cards on the sampling line showing spray deposit densities greater than about 12 drops per square centimeter. Thus, even though spray deposit density within the swath for Trial 7 was less, for example, than for Trial 6, the mass recovery for Trial 7 is greater than for Trial 6 because the swath is about four times as wide.

The higher percentage error made in estimating mass recovery from the 5-card analysis procedure for Trial 7 may be a combined result of the lower spray

TABLE 4-5

MASS RECOVERIES ESTIMATED FROM THE MASS DISTRIBUTION FROM 5 AND ALL CARDS IN THE SWATH

| Trial Number | Mass Recovery ($g\,m^{-1}$) | |
|---|---|---|
| | All Cards | 5 Cards |
| 6 | 17.3 | 18.2 |
| 7 | 26.6 | 33.9 |
| 9 | 5.02 | 5.98 |
| 11 | 4.57 | 4.10 |
| 18 | 4.92 | 4.41 |

deposit density and the fact that a lower percentage of cards in the swath (5 of 31 total cards) were analyzed than in the case of other trials.

## Summary

Rapid estimates of the minimum swath width and spray deposit density within the swath can be made in the field immediately after the aircraft flight by counting stains on one sampling card on each end of the sampling line. Rapid estimation of the volume median diameters using the D-max method is recommended for use in the field.

Results of the post-trial analysis of data from 5 of the Townsend trials indicates that quantitative estimates of the volume median, number median and average mass diameters can be developed within a 5-hour period after flight time from cumulative mass and number distributions based on the analysis of 5 cards within the swath. Errors in estimating these parameters from an analysis of 5 rather than all cards in the swath were less than 10 percent. Thus, procedures for estimating the volume median, number median and average mass diameters from the analysis of 5 sampling cards are recommended in the field manual.

As might be expected from the cubic relationship between drop diameter and mass recovery and the other approximations used in the 5-card analysis procedure, percentage errors in estimating mass recovery using this procedure are greater than experienced in estimating the other spray characteristics. However, because the analysis of trial data must be completed on a timely basis, the 5-card analysis procedure is recommended for use in the field manual in estimating mass recovery.

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Maksymiuk, Bohdan, 1964: A rapid method for estimating the atomization of oil-base aerial sprays. Journal of Economic Entomology, Volume 57, No. 1, p. 16.

TABLE OF CONTENTS


| Section | Title | Page |
|---|---|---|
| 1 | INTRODUCTION | 1 |
| | 1.1 Background | 1 |
| | 1.2 Study Objectives | 1 |
| | 1.3 Report Contents | 3 |
| 2 | DESCRIPTION OF THE TOWNSEND SPRAY CHARACTERIZATION TRIALS | 4 |
| | 2.1 Design of the Sampling Grid for the Townsend Trials | 6 |
| | 2.2 Stain Factors | 8 |
| | 2.3 Field Analysis Procedures | 8 |
| | 2.4 Meteorological Data | 13 |
| | 2.5 Field Laboratory Analysis Procedures | 16 |
| 3 | POST-TRIAL ANALYSIS | 20 |
| | 3.1 Determination of Spray Deposit Densities on Sampling Cards and Swath Width | 22 |
| | 3.2 Determination of Drop-Size Distribution by Number and Mass Number Median and Volume Median Diameters | 31 |
| | 3.3 Mass Recovery Estimates | 39 |
| 4 | DEVELOPMENT OF A FIELD MANUAL | 54 |
| | 4.1 Designing the Sampling Grid and Operational Considerations | 54 |
| | 4.2 Analysis of Sampling Card Data | 65 |
| | REFERENCES | 76 |

TABLE OF CONTENTS (Continued)


| Appendix | Title | Page |
|---|---|---|
| A | FIELD MANUAL FOR CHARACTERIZING SPRAY FROM SMALL AIRCRAFT | A-1 |
| B | WIND MEASUREMENTS | B-1 |
| C | FIELD LABORATORY ESTIMATES OF SPRAY DEPOSIT DENSITIES | C-1 |

# SECTION 1
# INTRODUCTION

## 1.1 BACKGROUND

The U. S. Forest Service utilizes contractor-supplied and -operated aircraft for the aerial application of pesticides during most forest spray projects. The effective utilization of aircraft spray systems requires, among other things, that basic parameters affecting spray deposit patterns such as flow rate, drop-size distribution and aircraft altitude be accurately adjusted for each spray operation. There are a number of important logistical constraints affecting the field measurements of spray pattern characteristics. For example, because of cost factors, the spray aircraft is normally scheduled to be available at the site of the spray project only a few days prior to the commencement of spray operations. Thus, the time available for quantifying spray characteristics and making any required adjustments is very short.

In recognition of the need to develop quantitative field procedures for the rapid characterization of spray patterns, the Methods Application Group (MAG) and the Missoula Equipment Development Center (MEDC), Forest Service, USDA, initiated a field program in conjunction with the Northern Region 1976 Pilot Project to develop and evaluate spray characterization procedures. A contractor, the H. E. Cramer Company, Inc. assisted MEDC in the development and evaluation of these during the Northern Region 1976 Pilot Project.

## 1.2 STUDY OBJECTIVES

The specific objectives of the work performed for MEDC by the H. E. Cramer Company were to:

(1) Establish procedures to achieve reproducible deposits on deposit card samplers and to estimate the number of spray drops per square centimeter, volume median diameter, number median diameter, mass per unit area and minimum effective swath width from deposit card sampler data.

(2) Establish methods and procedures and recommend the equipment required to enable two or three persons to complete the characterization of aircraft spray within 5 hours following a field trial.

(3) Evaluate the methods, procedures and equipment used in the Northern Region 1976 Pilot Project at Townsend, Montana.

The factors to be considered in the development of a field methodology for characterizing small aircraft spray included the following:

- Advantages of inwind flight patterns versus crosswind flight patterns
- Meteorological limitations imposed on the conduct of field trials
- Optimum flight altitude of the aircraft
- Minimization of grid sampler requirements
- Optimum arrangement of card samplers

- The times or points at which the aircraft spray system should be turned on and turned off during a characterization flight

## 1.3 REPORT CONTENTS

This technical report describes the spray characterization trials conducted during the Northern Region 1976 Pilot Project at Townsend, Montana; the post-trial analysis of the sampler card and meteorological data obtained during the Townsend trials; and, the background for the development of the field manual for characterizing spray from small aircraft. Section 2 below describes the characterization trials at Townsend, including the design of the sampling grid as well as the "quick-look" field analysis and field laboratory analysis of the sampler card data. The procedures used in the post-trial data analysis and the results of this analysis are described in Section 3. Section 4 presents the detailed background of the development of the field manual for characterizing spray aircraft. There are three appendices to the report. The "Field Manual for Characterizing Spray from Small Aircraft" developed as a result of this study is reproduced in Appendix A. Appendix B contains summary tables of wind direction and wind speed measured during the characterization trials. Estimates of the spray deposit density made during the laboratory analysis of all sampler cards in the spray swath at Townsend are contained in Appendix C.

## SECTION 2

## DESCRIPTION OF THE TOWNSEND SPRAY CHARACTERIZATION TRIALS

The Townsend spray characterization trials were conducted from 27 through 30 June, 1976, in an area north of Townsend adjacent to the Silos Recreation Area, using a Bell 205 helicopter equipped for aerial spray applications. As shown in Table 2-1, there were a total of 19 trials. An Orthene mix was used in 8 trials while a Dylox mix was used in the remaining 11 trials. The Orthene was prepared for spraying by using 1.33 pounds of Orthene, 0.01 pounds of Rhodamine B dye and 0.885 gallons of water to make one gallon of spray. One-half gallon of Dylox liquid, 0.48 gallon of Hi Sol 4-5-T solvent and 0.02 gallon of Automate Red B dye were used to make one gallon of the Dylox spray mix. As noted in Table 2-1, the aircraft flight altitude was 50 feet above the ground in all trials except Trial 7, where the flight altitude was 100 feet. Eight Beecomist spray heads were used in the first 11 trials and in Trial 14. Four heads were placed on the booms on each side of the helicopter at distances of 8, 14, 20 and 24 feet from the centerline of the helicopter. Four Beecomist spray heads were used in Trials 12 and 13, two on each side of the helicopter at distances of 8, 14, 20 and 24 feet from the centerline of the aircraft. The Beecomist spray heads were calibrated at the site to deliver a total of 36.4 gallons per minute of Orthene and 18.2 gallons per minute of Dylox, regardless of the number of heads used. A total of 31 Spraying Systems Flat Fan Spray Tip Nozzles No. 8006 were used on Trial 15; the nozzles were equally spaced with 16 nozzles on the right spray boom and 15 on the left spray boom. Nineteen Spraying Systems Flat Fan Spray Tip Nozzles No. 8010 were used on the remaining trials with 10 nozzles equally spaced on the right boom and 9 on the left boom. The flat fan nozzles were not field calibrated for flow rate, but were set to deliver a total flow rate of 18.2 gallons per minute of Dylox, according to factory specifications, for each of the trials.

TABLE 2-1

BASIC SPRAY DATA FOR THE TOWNSEND CHARACTERIZATION TRIALS

| Trial Number | Date | Time (MDT) | Aircraft Height (ft) | Spray Material | Spray Nozzles | Total Flow Rate (gal $min^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | 6/27 | 0617 | 50 | Orthene | 8 Beecomist | 36.4 |
| 2 | 6/27 | 0715 | 50 | Orthene | 8 Beecomist | 36.4 |
| 3 | 6/27 | 0902 | 50 | Orthene | 8 Beecomist | 36.4 |
| 4 | 6/27 | 1013 | 50 | Orthene | 8 Beecomist | 36.4 |
| 5 | 6/27 | 2048 | 50 | Orthene | 8 Beecomist | 36.4 |
| 6 | 6/28 | 0613 | 50 | Orthene | 8 Beecomist | 36.4 |
| 7 | 6/28 | 0755 | 100 | Orthene | 8 Beecomist | 36.4 |
| 8 | 6/28 | 0850* | 50 | Orthene | 8 Beecomist | 36.4 |
| 9 | 6/28 | 2036 | 50 | Dylox | 8 Beecomist | 18.2 |
| 10 | 6/28 | 2114 | 50 | Dylox | 8 Beecomist | 18.2 |
| 11 | 6/29 | 0537 | 50 | Dylox | 8 Beecomist | 18.2 |
| 12 | 6/29 | 0656 | 50 | Dylox | 4 Beecomist | 18.2 |
| 13 | 6/29 | 0753 | 50 | Dylox | 4 Beecomist | 18.2 |
| 14 | 6/29 | 0835 | 50 | Dylox | 8 Beecomist | 18.2 |
| 15 | 6/29 | 2019 | 50 | Dylox | 31 Flat Fan No. 8006 | 18.2 |
| 16 | 6/29 | 2104 | 50 | Dylox | 19 Flat Fan No. 8010 | 18.2 |
| 17 | 6/30 | 0624 | 50 | Dylox | 19 Flat Fan No. 8010 | 18.2 |
| 18 | 6/30 | 0708 | 50 | Dylox | 19 Flat Fan No. 8010 | 18.2 |
| 19 | 6/30 | 0830 | 50 | Dylox | 19 Flat Fan No. 8010 | 18.2 |

*Approximate time of trial (actual time not recorded but known to be within the hour following Trial No. 7).

Because the spray lines were not purged of water for Trial 1, the sampler cards for Trial 1 were not analyzed. Also, it was noted that the flat fan nozzles used on Trial 16 were oriented at various angles to the horizontal. In the subsequent trials, the nozzle attitudes were changed so that the 6 tips on the outboard section of the right boom and 5 tips on the outboard section of the left boom were directed straight down (90 degrees to the horizontal). The remaining 4 tips on the inboard section of the left and right booms were oriented forward and down at an angle of 45 degrees from the horizontal.

All trials were conducted with the helicopter flying into the wind except for Trial 8, where the flight path was crosswind. The helicopter flew at an air speed of 90 miles per hour on all trials.

## 2.1 DESIGN OF THE SAMPLING GRID FOR THE TOWNSEND TRIALS

Figure 2-1 shows a map of the sampling grid which was located north of Townsend in a large field between Montana Highway 12 and the Silos Recreation Area just east of the shore of Canyon Ferry Lake. It should be noted that sampling line C was moved to the position shown in Figure 2-1 prior to Trial 5. For the first four trials, sampling line C was oriented north-south with its northern extremity at the middle of sampling line B. The final grid configuration shown in Figure 2-1 was designed to take advantage of the wind directions expected to occur over the site during the characterization trials in which the helicopter released material while flying into the wind. Sampling line A was nominally oriented east-west for use when the wind directions were either up- or down-valley parallel to the shoreline of Canyon Ferry Lake. Sampling line B was oriented southwest-northeast for use when the winds were downslope through a pass located northwest of the site. Sampling Line C was moved to the location shown in Figure 2-1 after it became evident that advantage should be taken of the weak downslope flow from the mountains west of the site and weak upslope flow from Canyon Ferry Lake.

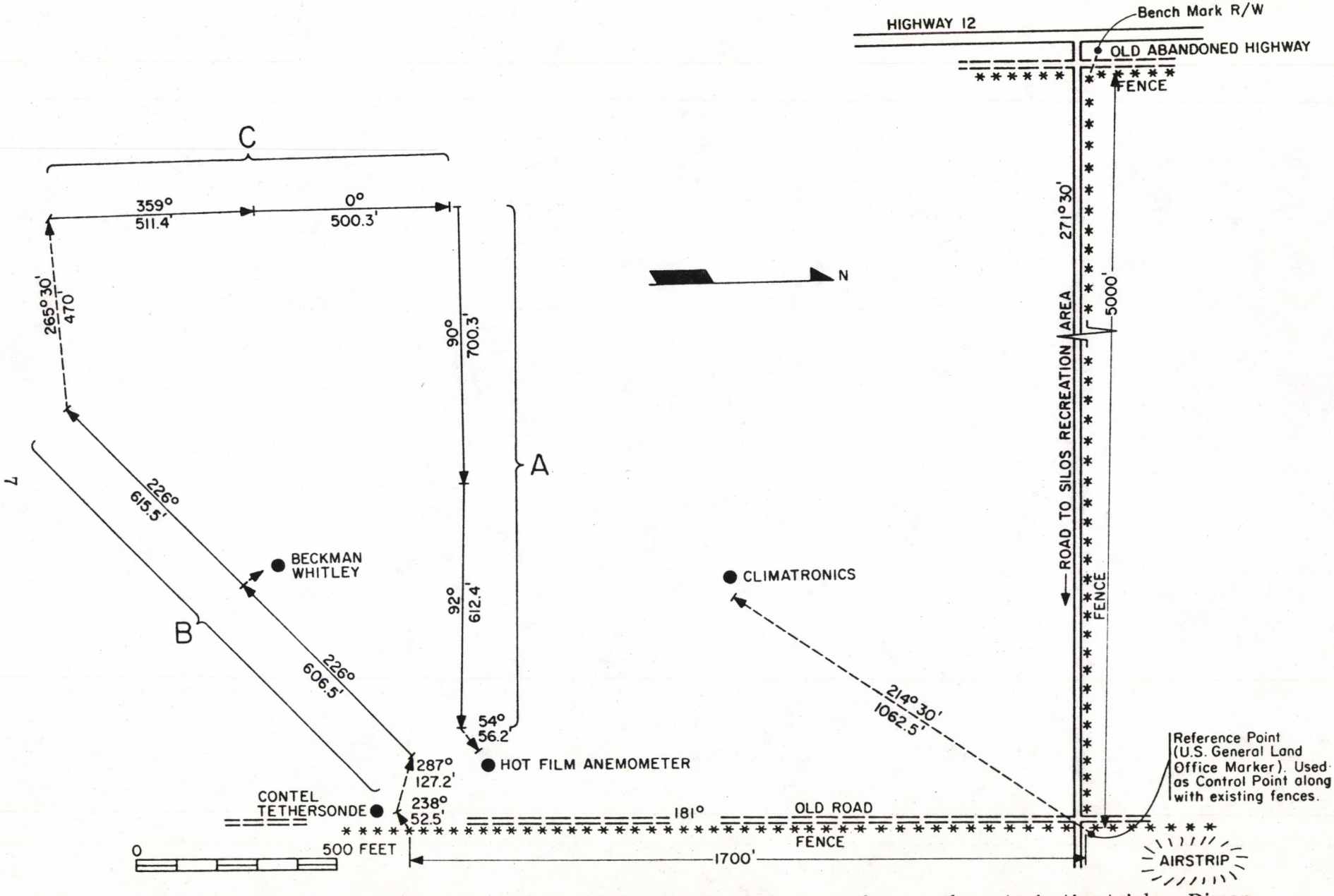



FIGURE 2-1. Schematic diagram of the sampling grid for the Townsend spray characterization trials. Dimensions are in feet.

## 2.2 STAIN FACTORS

The following equations for converting the diameters of stains observed on Kromekote cards, used in the Townsend Trials, to diameters of the drops impacting on the cards were obtained in a laboratory analysis conducted by the Department of Agricultural Engineering, University of California, Davis Campus, under contract to MAG:

Orthene Spray

$$y = -8.3 \times 10^{-5} x^2 + 0.47x + 37.6 \qquad (2\text{-}1)$$

Dylox Spray

$$y = 5.73 \times 10^{-6} x^2 + 0.199x + 7.68 \qquad (2\text{-}2)$$

where

y = drop diameter in micrometers

x = stain diameter in micrometers

A separate study conducted by John Barry and Lynne Whitcombe of MAG showed that no significant increase in stain diameters occurred beyond 5 minutes of elapsed time after drop impact on the sampler cards.

## 2.3 FIELD ANALYSIS PROCEDURES

A "quick-look" field analysis to estimate volume median drop diameter and swath width for each trial was initiated in the field 5 to 10 minutes after drops from the spray cloud were no longer impacting on the Kromekote cards. A "direct-estimation" method was used to estimate the characteristic volume median diameter

(VMD) for each trial. The D-max procedure developed by Maksymiuk (1964), although suitable for use as a "quick-look" method and applied after some trials in the field, was used more frequently in the field laboratory analysis and is described in Section 2.4 below.

The direct-estimation procedure was suggested for use in estimating VMD's for the Townsend Trials and was used with success by Mr. William McIntyre, Dugway Proving Ground, Dugway, Utah. Mr. McIntyre has developed the talent of observing a drop-stained card and visually selecting the stain representing the VMD for a given card. As might be expected from the cubic relationship between the diameter and volume of a sphere, the drop stain representing the VMD is slightly larger than the average size of stains appearing on the card. Prior to and during the Townsend Trials, Mr. McIntyre trained two personnel from the H. E. Cramer Company in applying his visual estimation technique. It appears that about one week of working with an experienced instructor and drop-stained cards is required to become proficient in estimating the VMD using this technique. The major drawback of the method is that training is required before confidence can be placed in the VMD estimates. The major advantage is that, once the technique is mastered, VMD estimates are rapidly obtained.

In the Townsend Trials, the VMD was estimated in the field using the direct-estimation technique and a sampler card from the swath on the sampling line most nearly perpendicular to the aircraft flight path. The card was selected by walking along the card line and visually observing the density of stains on each card and selecting one card from the line judged to be of the density in the center of the swath. Usually, the card selected was near the center of the swath. The direct-estimation technique was then used to choose the stain on the selected card which represented the VMD. The diameter of the stain was measured to the nearest 50 micrometers using a Bausch and Lomb measuring magnifier (Catalog No. 80-34-35) with 100-micrometer divisions. The appropriate stain-drop relationship described in Sec-

tion 2.2 was applied and the VMD field estimate entered on a form similar to the example "Rapid Inspection Data Sheet" shown in Figure 2-2. The swath width was also visually estimated in a similar manner by selecting the first cards from either end of the swath where the stain density became uniform. The VMD for these cards was estimated using the procedure outlined above. The average mass diameter (AMD) was estimated using the following expression, which assumes that the drop-size distribution is log-normally distributed:

$$\ln (\text{AMD}) = \ln (\text{VMD}) - 1.5 \ln^2 \sigma_g \qquad (2\text{-}3)$$

where

$\sigma_g$ = geometric standard deviation of the drop-size distribution

An assessment of sampling card data from previous trials conducted by the Forest Service using Bell 205 helicopters showed that a value for $\sigma_g$ of 1.5 was best suited for use in the Townsend Trials. It should be noted that the relationship between AMD and VMD is sensitive to the value of $\sigma_g$. For this reason and because the distribution is often not strictly log-normal, this procedure is not recommended for use in the field manual given in Appendix A. The mass of the AMD drop in milligrams $\overline{m}$ (Drop Mass in Figure 2-2) was obtained from the relationship

$$\overline{m} = \frac{\pi \rho (\text{AMD})^3}{6} \times 10^{-9} \qquad (2\text{-}4)$$

where

$\rho$ = density of the spray material in grams per cubic centimeter

| | | | | | |
|---|---|---|---|---|---|
| Test | 2 | Air Speed | 90 mph | Spray Material | Orthene |
| Date/Time | 27 June 76/0715 MDT | Flow Rate | 36.4 gal $min^{-1}$ | Material Density | 1.044 |
| Aircraft | 205 | Flight Level | 50 feet | Row Number | B |

Card Number for VMD 61

Estimated VMD: Stain 450 $\mu$m Actual 232 $\mu$m

| SWATH WIDTH | |
|---|---|
| Left Card Number 77 | Right Card Number 57 |
| VMD: Stain 250 $\mu$m Actual 150 $\mu$m | VMD: Stain 600 $\mu$m Actual 290 $\mu$m |
| Average Mass Drop Diameter 117 $\mu$m | Average Mass Drop Diameter 226 $\mu$m |
| Drop Mass $8.7 \times 10^{-4}$ mg | Drop Mass $6.3 \times 10^{-3}$ mg |
| Number of Drops 240 | Number of Drops 65 |
| Density 131 mg $m^{-2}$ | Density 255 mg $m^{-2}$ |

FIGURE 2-2. Rapid Inspection Data Sheet used in the field at Townsend trials to estimate VMD and swath width.

As indicated in Figure 2-1, each line was greater than 1000 feet in length. A dispersion-modeling experiment prior to the start of the trials indicated that a sampler spacing of 10 feet would be more than adequate to ensure that at least 10 to 20 cards would be included within the expected swath width. For this reason, sampler card positions were marked at 10-foot intervals along all three sampling lines. For the first four trials, the sampling cards were mounted in plastic holders on metal stakes about 1.5 feet above the ground. This procedure was used because it is often more convenient to elevate the cards above surrounding grass clumps and other obstructions and because a previous experiment conducted by MEDC with a different spray material had indicated that there was no significant difference between characterization parameters measured on elevated cards and cards placed on the ground. After the first five trials, it became evident that the narrow elongated drop stains were due to the wind transport of the drops causing them to impact on the elevated cards at an oblique angle. In Trial 5, stains on cards placed on the ground in cleared areas close to a few elevated samplers on the stakes were nearly circular, probably because wind speeds close to the ground are light and the trajectory of the drops was more nearly perpendicular to the ground. The sampling cards in their plastic holders were placed on the ground in cleared areas next to the metal stakes on all succeeding trials. The sampling positions were numbered sequentially on each sampling line starting at the east end of line A, the northeast end of line B, and the north end of line C.

Climatronics Corporation and Beckman-Whitley sensors were used at the positions shown in Figure 2-1 to measure wind direction and wind speed at 2 meters above the ground. Measurements of wind direction, wind speed, temperature and relative humidity were made to altitudes of 100 feet using a balloon-borne sensor (tethersonde) and associated recording equipment, manufactured by Contel Corporation, at the position shown at the east end of sampling line B. A hot-film anemometer held aloft by a pilot balloon was used at a position near the east end of sampling line A to measure winds at an altitude of 50 feet.

The density $\rho$ of the Orthene spray material was 1.044 g $cm^{-3}$ and the density of the Dylox material was 1.067 g $cm^{-3}$.

The spray deposit density on the cards representing the edges of the swath was estimated by counting stains with a hand-held magnifying glass and a clear plastic template similar to the template shown in Figure 2-3. In the Townsend Trials, the stains were first counted in the small (1 square centimeter) square in the upper left corner of the template. If the number of stains counted in this square exceeded 50, no further counting was done on the card. If less than 50 stains were counted, additional squares were counted until the total of stains counted exceeded 50. The mass density of the drops on the card was then estimated from the expression

$$\text{Mass Density} = M = \frac{m \times \text{Number of Stains Counted}}{\text{Number of Squares Counted}} \qquad (2\text{-}5)$$

and the result entered on the Rapid Inspection Data Sheet. The entries on the data sheet were then reviewed with the project director.

Table 2-1 contains the volume median diameters and swath widths estimated in the field during the Townsend Trials.

## 2.4 METEOROLOGICAL DATA

The H. E. Cramer Company was supplied with the strip charts containing the wind directions and wind speeds measured by the Beckman and Whitley sensors and Climatronics sensors at a height of 2 meters. The mean wind directions and wind speeds measured at the two instrument locations (see Figure 2-1) did not differ significantly. The recorders used with the Beckman and Whitley sensors were operated at a higher chart speed, thus permitting 30-second average wind directions and speeds to be abstracted from the charts. Appendix B contains tables of the 30-

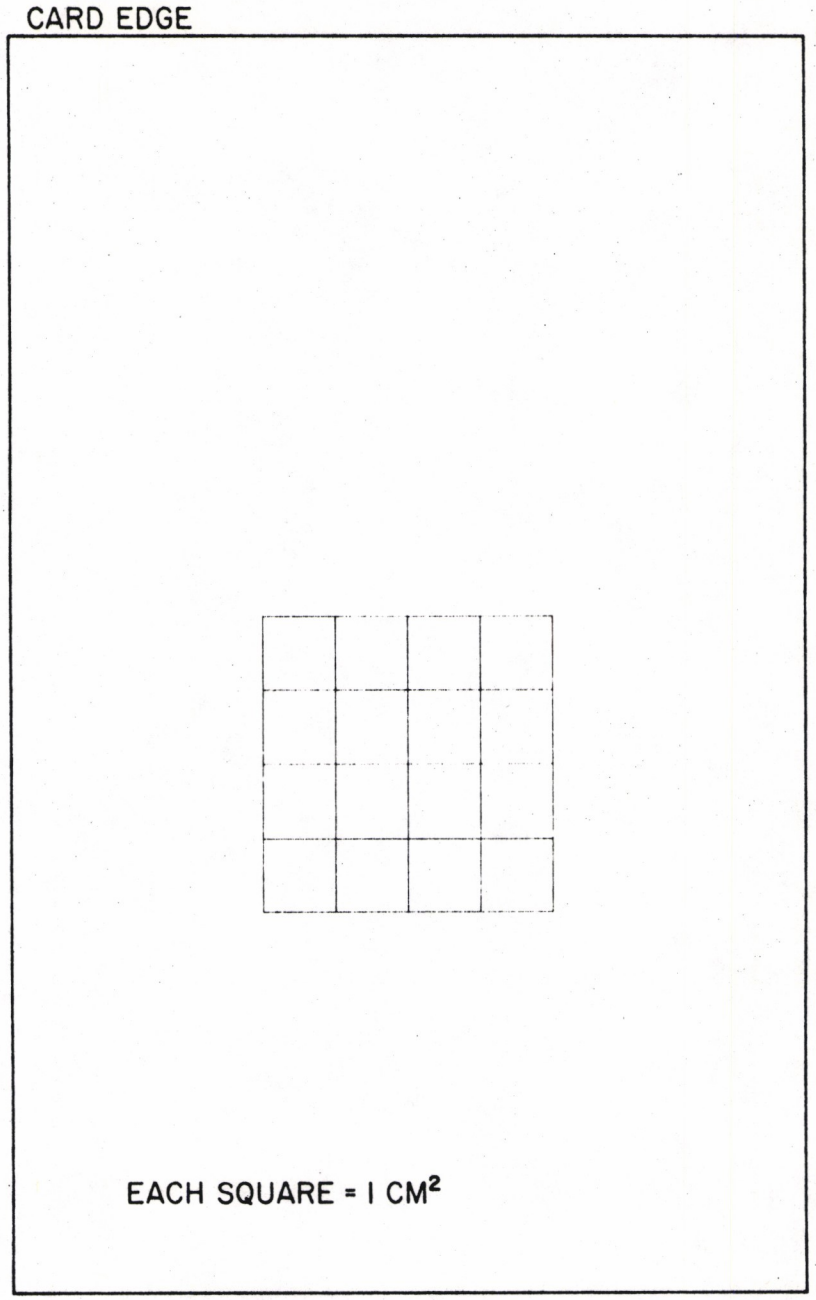



FIGURE 2-3. Template for counting of drops on sampler cards in the field.

This report is published as part of a Forest Service program to improve aerial application of insecticides, specifically by using insecticides and delivery systems tailored to the forest environment. The program is being conducted jointly by the Equipment Development Center, Missoula, Mont., and Methods Application Group, Davis, Calif., under the sponsorship of the Forest Insect and Disease Management Staff. Information or questions regarding this work should be directed to:

WO-FIDM
Methods Application Group
2810 Chiles Rd.
Davis, Calif. 95616

*A report on Equipment Development and Test Project 7069, Characterization of Small Spray Aircraft funded by the Forest Insect and Disease Management Staff.*

TABLE 2-1

VOLUME MEDIAN DIAMETERS (VMD) AND
SWATH WIDTHS ESTIMATED IN
THE FIELD DURING THE
TOWNSEND TRIALS

| Trial Number | VMD (micrometers) | Swath Width (feet) | Sampling Line Used |
|---|---|---|---|
| 2 | 232 | 200 | B |
| 3 | 232 | 180 | C |
| 5 | 252 | 160 | B |
| 6 | 212 | 170 | B |
| 7 | 212 | 420 | A |
| 9 | 109 | 180 | C |
| 10 | 109 | 380 | B |
| 11 | 119 | 260 | A |
| 12 | 150 | 240 | C |
| 13 | 150 | 110 | A |
| 14 | 119 | 240 | C |
| 15 | 140 | 150 | B |
| 16 | 150 | 200 | B |
| 17 | 170 | 210 | B |
| 18 | 150 | 230 | B |
| 19 | 129 | 220 | A |

second average wind data obtained from these records for approximately a 5-minute period beginning 5 seconds before the helicopter passed over the sampling line.

## 2.5 FIELD LABORATORY ANALYSIS PROCEDURES

The forest Service arranged for space in the Townsend grade school for use as a field laboratory in carrying out a more detailed analysis of the sampling cards than was possible in the field. The sampling cards were returned to the school after each morning and evening set of trials. Two procedures were used in the field laboratory to estimate the VMD characteristic of each trial. These were variations of the direct-estimation procedure described in Section 2-3 above and D-max method described by Maksymiuk (1964).

The direct-estimation method was used to estimate the VMD on each card within the swath. The VMD characteristic of the trial was then obtained by calculating a mass weighted VMD from the expression

$$VMD = \frac{\sum_{j=1}^{N} VMD_j \left(M_j\right)}{\sum_{j=1}^{N} \left(M_j\right)} \qquad (2\text{-}6)$$

where

$VMD_j$ = VMD estimated for the $j^{th}$ card in the sampling line

$M_j$ = mass density from Equation (2-5) for the $j^{th}$ card in the sampling line

N = total number of cards analyzed

A value of 1.5 for $\sigma_g$ was again used in Equation (2-3) to estimate the AMD from the BMD estimated for each of the cards.

The D-max method was applied in the following stepwise procedure:

(1) The largest stains on each card in the swath width were measured to the nearest 50 micrometers using the Bausch and Lomb measuring magnifier.

(2) The stain diameters were converted to drop diameters using the appropriate relationship for Orthene or Dylox given in Section 2.2.

(3) The five largest measured drop diameters were arranged in ascending order. If two or more drops were of the same size, they were counted as separate drops and listed sequentially in the list of the five largest drops.

(4) Beginning with the smallest drops in the list, the difference in diameter between sequentially listed drops was noted. If no difference between sequential diameters in the list was greater than 32 micrometers, the largest drop was used in Step 5 below. If a difference greater than 32 micrometers, the diameter of the drop just below the point where the difference in diameters exceeded 32 micrometers was used in Step 5 below.

(5) The drop diameter selected in Step 4 above was divided by a factor of 2.2 to obtain the estimate of $\overline{\text{VMD}}$ characteristic of the trial.

This D-max procedure was applied in the field laboratory by John Barry and Lynne Whitcombe of MAG for 11 of the 16 trials analyzed. To check the ease of application of the method and the reproducibility of the estimates using different analysts, the D-max method was reapplied at the H. E. Cramer Company in Salt Lake City after the trials were completed. The results obtained in the field, using both the direct-estimation procedure and the D-max methods, and in the post-trial analysis using the D-max method are given in Table 2-2. Comparison of the VMD estimates obtained by the direct-estimation procedure and the D-max method shows that, in every case, the D-max method applied in the field yielded larger values of VMD. The field and post-trial D-max estimates of VMD show good agreement. Sampling card data for Trials 6, 7, 9, 11 and 18 were analyzed in greater detail during the post-trial analysis described in Section 3 below, including estimation of VMD from a cumulative drop-size distribution for all cards in the swath.

The density of drops per square centimeter for each card in the swath was also estimated in the field laboratory for the trials listed in Table 2-2, using the counting procedure outlined in Section 2.3, a template similar to that shown in Figure 2-3 and the Bausch and Lomb magnifier rather than the large magnifying glass used in the field. The spray deposit densities obtained in this analysis are given in tabular form in Appendix C.

TABLE 2-2

LABORATORY ESTIMATES OF VMD BY THE DIRECT-ESTIMATION AND D-MAX METHODS

| Trial Number | Direct Estimate of VMD ($\mu$m) | D-Max Estimate of VMD ($\mu$m) | |
|---|---|---|---|
| | | Field | Post-Trial |
| 2 | 217 | 219 | |
| 3 | 227 | 262 | |
| 5 | 206 | 231 | |
| 6 | 223 | 236 | 206 |
| 7 | 202 | 206 | 200 |
| 9 | 114 | 155 | 145 |
| 10 | 102 | | 135 |
| 11 | 101 | 149 | 145 |
| 12 | 134 | 175 | 155 |
| 13 | 134 | | 145 |
| 14 | 106 | 135 | 135 |
| 15 | 114 | 126 | 125 |
| 16 | 133 | 155 | 165 |
| 17 | 121 | | 155 |
| 18 | 112 | | 145 |
| 19 | 109 | | 125 |

## SECTION 3

## POST-TRIAL ANALYSIS

The only valid means of confirming the estimates of the number of spray drops per square centimeter, volume median diameter, and the mass deposited on the sampling cards made during the Townsend trials was to perform a more complete analysis after the trials, including the development of volume and number cumulative distributions for selected trials. The additional analyses were also required to reach decisions regarding the types of procedures that could be recommended for use in the field to obtain the best rapid estimates of spray characterization parameters.

To ensure that reproducible results could be obtained, the decision was made to perform the post-trial analysis in duplicate. Arrangements were made by MEDC with Dugway Proving Ground to have Mr. McIntyre count and size stains for selected trials. Mr. William Santee of the H. E. Cramer Company was assigned the task of counting and sizing stains for the same trials. Because of the limited time and funds available for the post-trial analyses, data from only 5 trials could be analyzed in the requisite detail. Two trials where the Orthene mix was sprayed and 3 where the Dylox mix was sprayed were selected for analysis. Trials 6 and 7 were chosen for the Orthene mix because these trials were the only 2 trials where the aircraft flew into the wind and the drops were sampled using cards placed on the ground. Trials 9 and 11 were chosen because the standard configuration of 8 Beecomist spray heads was used and the aircraft flight path into the wind was nearly perpendicular to the sampling line. Trial 18 was chosen because a standard configuration of 19 Flat Fan No. 8010 spray heads was used on the helicopter spray boom.

A plastic template similar to that shown in Figure 3-1 was used in both the counting and sizing of drop stains. One of the three template sizes of 4, 8 or

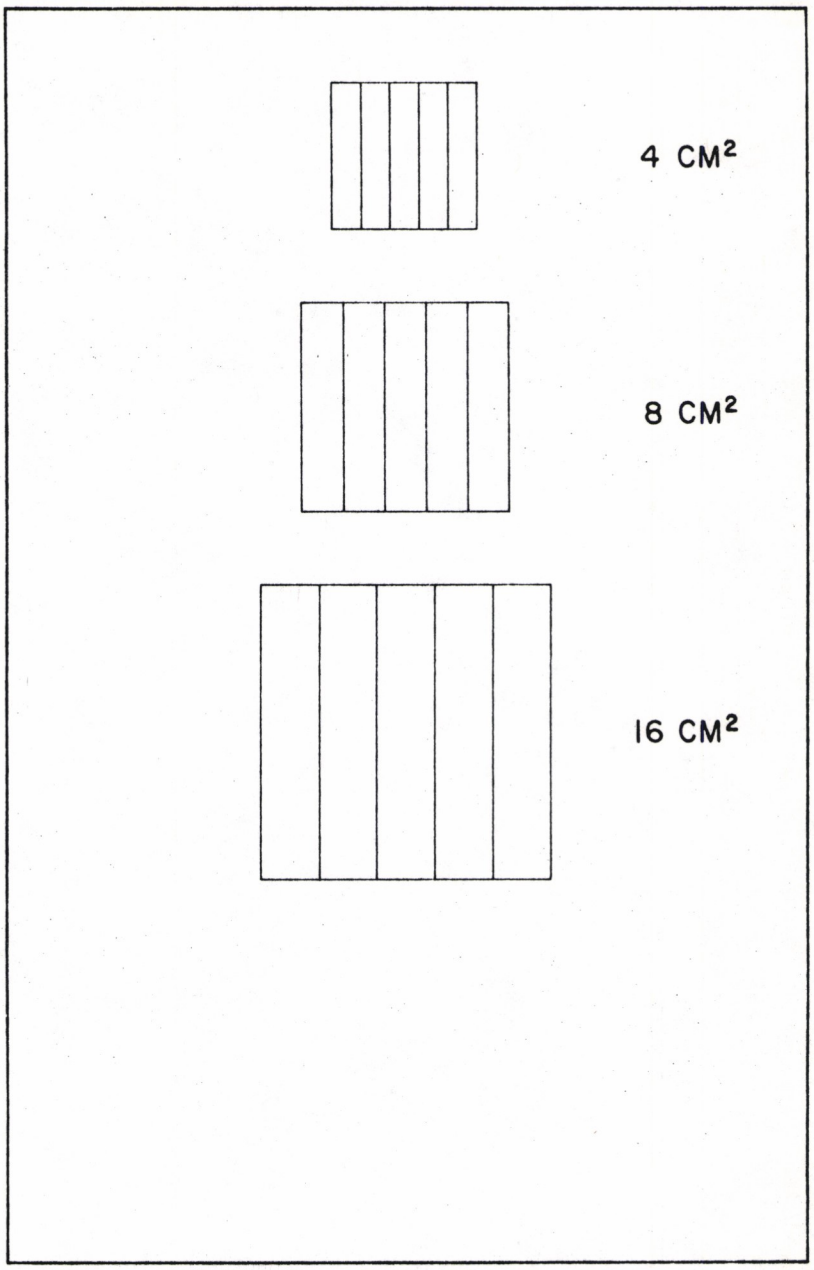



FIGURE 3-1. Template used for counting drops.

16 square centimeters was chosen, depending on visual inspection of the density of stains on a sampling card, for use in the counting and sizing of stains to ensure that a minimum of 200 stains were considered. Each stain diameter was measured and counted using the Bausch and Lomb measuring magnifier and assigned to one of 8-to-12 stain diameter categories. The upper limits of the stain diameter categories used in the analyses of the five trials are shown in Table 3-1. The drop diameters corresponding to the category limits shown in Table 3-1 were calculated from the stain-factor relationships given in Section 2.2.

## 3.1 DETERMINATION OF SPRAY DEPOSIT DENSITIES ON SAMPLING CARDS AND SWATH WIDTH

After the stains on the sampling cards from the sampling line used in the trial were counted and sized, the density of stains on each card was calculated from the expression

$$N_j = \frac{1}{A_j} \sum_{i=1}^{I} n_{i,j} \qquad (3\text{-}1)$$

where

$N_j$ = spray deposit density for the $j^{th}$ card in the line (drops $cm^{-2}$)

$A_j$ = area of the template counted for the $j^{th}$ card ($cm^2$)

$I$ = total number of stain size categories counted for the $j^{th}$ card

$n_{i,j}$ = number of drops counted in the $i^{th}$ drop size category on the $j^{th}$ card

TABLE 3-1

UPPER LIMITS IN MICROMETERS OF STAIN AND DROP-SIZE CATEGORIES USED IN THE POST-TRIAL ANALYSIS

| | | | Drop-Size Category | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial | Row | Upper Limit | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 6 | B | Stain | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | | |
| | | Drop | 83.77 | 128.3 | 171.1 | 212.3 | 251.8 | 289.7 | 325.9 | 360.5 | 393.4 | 424.6 | | |
| 7 | A | Stain | 100 | 200 | 300 | 400 | 500 | 600 | 800 | 1000 | | | | |
| | | Drop | 83.77 | 128.3 | 171.1 | 212.3 | 251.8 | 289.7 | 360.5 | 424.6 | | | | |
| 9 | C | Stain | 100 | 200 | 300 | 400 | 500 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | |
| | | Drop | 27.64 | 47.71 | 67.90 | 88.20 | 108.6 | 129.1 | 170.5 | 212.4 | 254.7 | 297.5 | 340.7 | |
| 11 | A | Stain | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | |
| | | Drop | 27.64 | 47.71 | 67.90 | 88.20 | 108.6 | 129.1 | 149.8 | 170.5 | 191.4 | 212.4 | 233.5 | |
| 18 | B | Stain | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 |
| | | Drop | 27.64 | 47.71 | 67.90 | 88.20 | 108.6 | 129.1 | 149.8 | 170.5 | 191.4 | 212.4 | 233.5 | 254.7 |

The results obtained by using Equation (3-1) to calculate spray deposit densities for the five selected trials are shown in Figures 3-2 through 3-6 for both observers. Inspection of the figures shows that one analyst consistently estimated higher densities than the other (counted more drops). We are unable to account with certainty for this consistent bias. It should, however, be noted that Mr. McIntyre and Mr. Santee did not necessarily count stains in the same location on the sampling card. Each analyst counted stains in the area he felt was representative of the observed density on each card. A possible explanation of the bias is that the analysts differed in their selection of the area of the card that was representative of the observed density, one analyst always selecting an area with a higher density than the other. To examine this possibility, the two analysts were asked to examine some cards and estimate spray deposit density after the analysis of the trials had been completed. The exact area to be counted was marked and both analysts counted the same area. The estimates of deposit densities by the two analysts were considerably closer, but some bias was still present. Areas on additional cards were marked and the analysts were asked to count only stains that were larger than 50 micrometers, since the measuring magnifier was marked in 100-micrometer intervals. The result of this experiment showed no bias between the two analysts. Sufficient time and funds were not available to undertake the recounting of all the cards to further examine the bias problem. However, in the field manual, the templates have been designed so that the same area is counted on all cards and the recommendation is made that stains less than 50 micrometers not be counted when the Bausch and Lomb measuring magnifier is used. If drops producing stains less than 50 micrometers are important in the estimate of drop density or mass deposition, a more accurate measurement device should be used.

The profiles of crosswind spray deposit density shown in Figures 3-2 through 3-6 can be used to estimate the minimum swath width based on spray deposit density. Estimates of the minimum swath width for five trials are shown in Table 3-2. Swath widths for all trials except Trial 7 were estimated as the distance between cards on

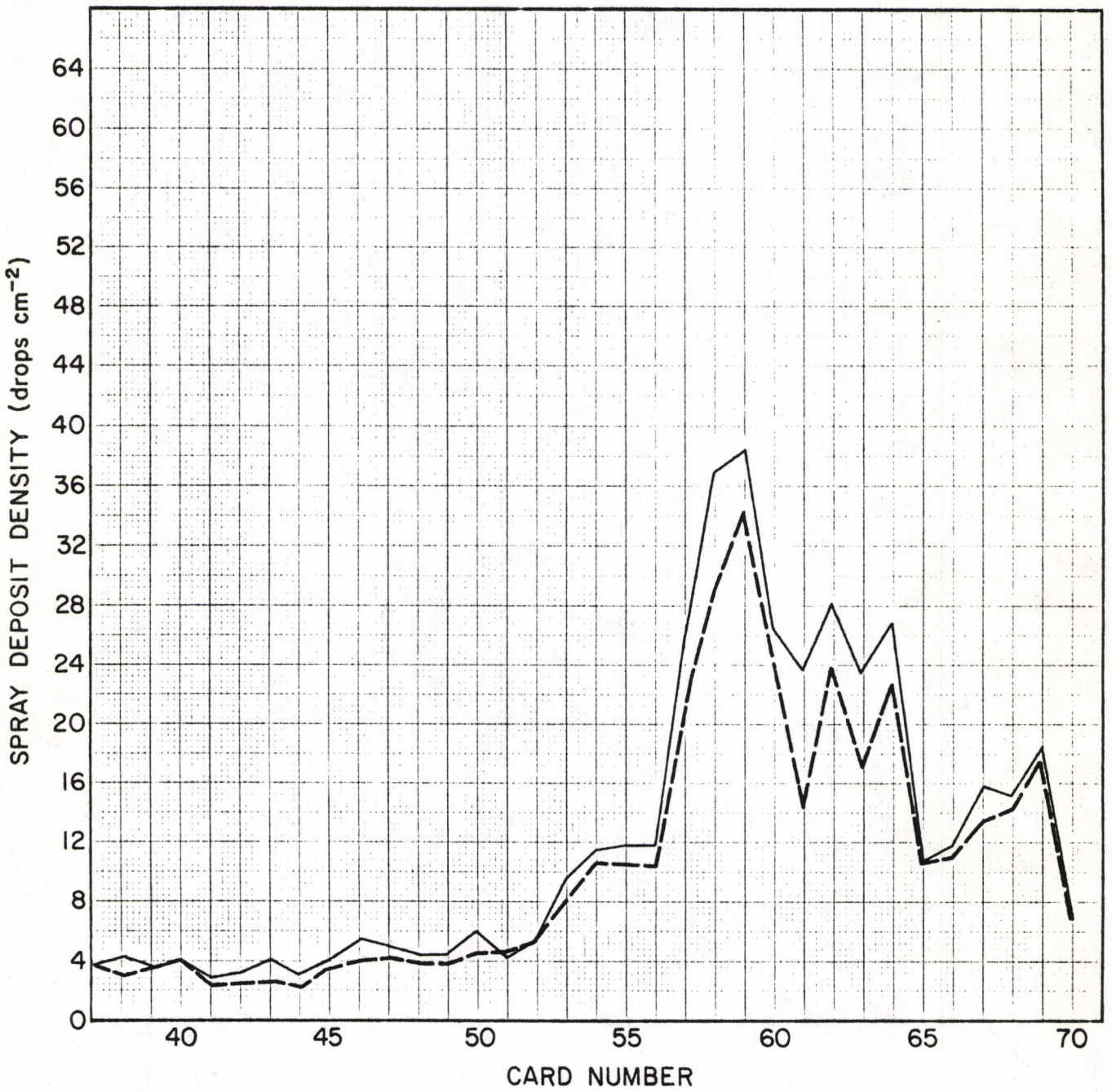



FIGURE 3-2. Spray deposit density for Trial 6. The dashed and solid lines represent results obtained by two different analysts.

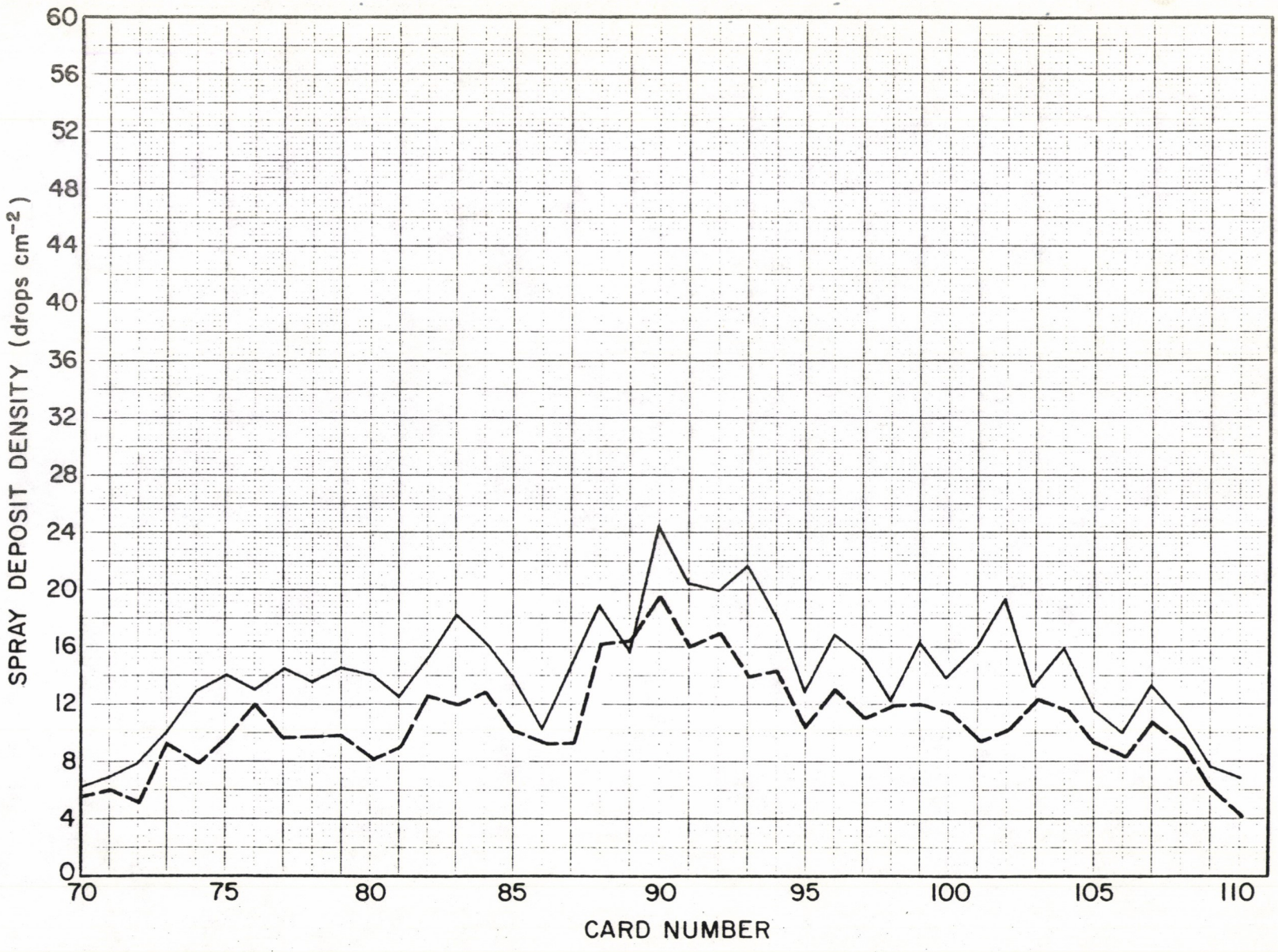



FIGURE 3-3. Spray deposit density for Trial 7. The dashed and solid lines represent results obtained by two different analysts.

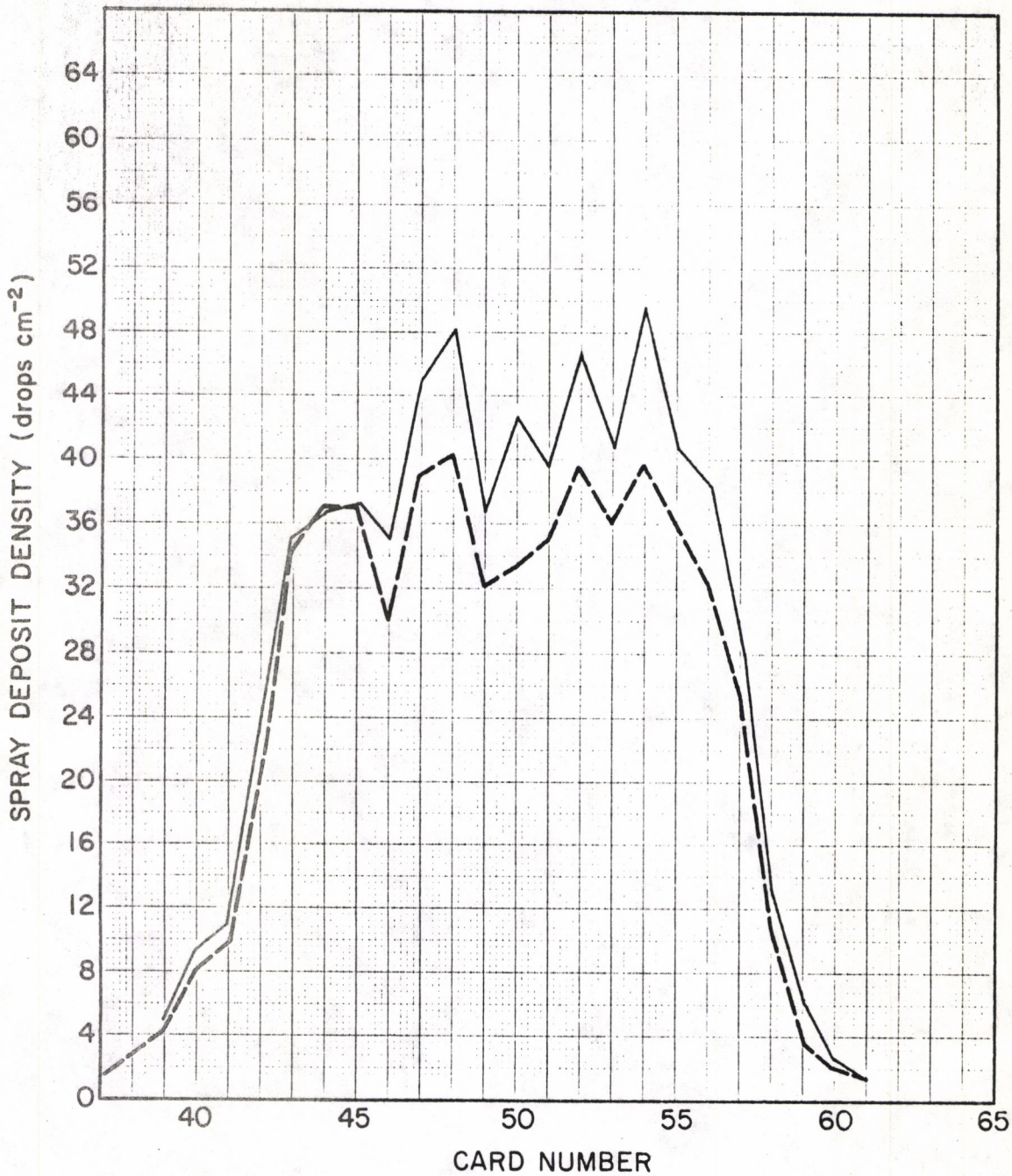



FIGURE 3-4. Spray deposit density for Trial 9. The dashed and solid lines represent results obtained by two different analysts.

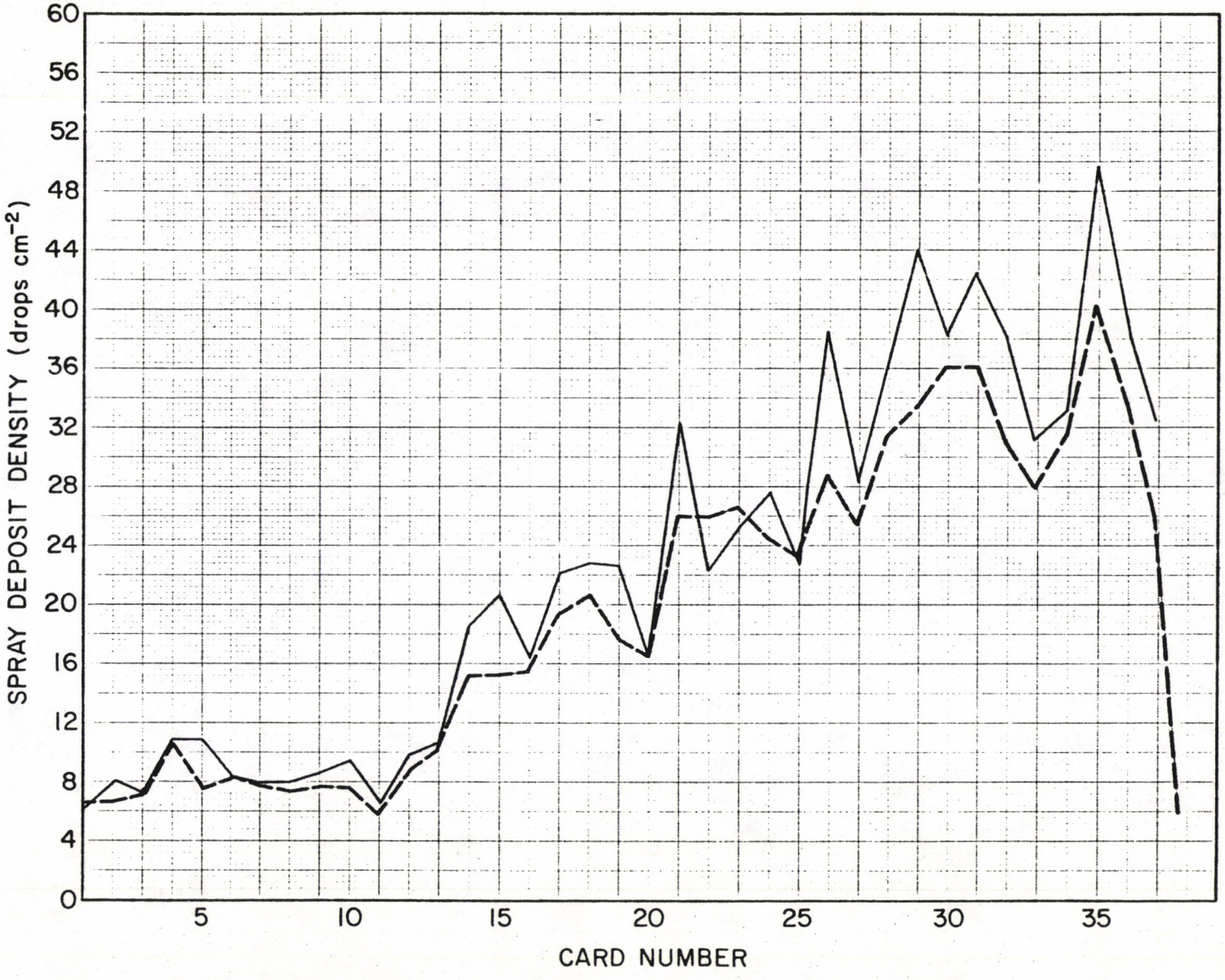



FIGURE 3-5. Spray deposit density for Trial 11. The dashed and solid lines represent results obtained by two different analysts.

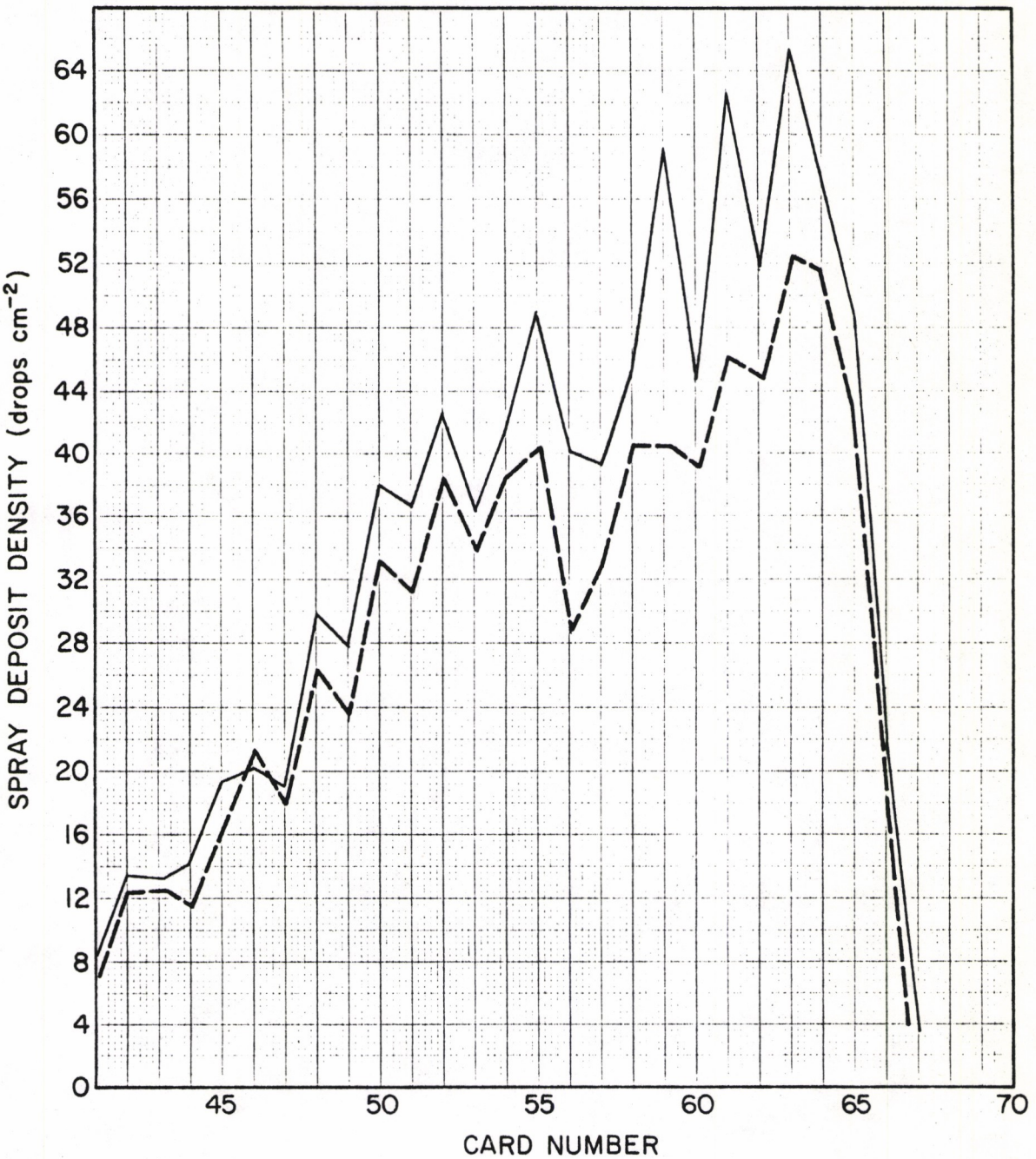



FIGURE 3-6. Spray deposit density for Trial 18. The dashed and solid lines represent results obtained by two different analysts.

# APPENDIX A

## FIELD MANUAL FOR CHARACTERIZING SPRAY FROM SMALL AIRCRAFT

This appendix contains a complete copy of the field manual developed under the contract.

plotting mass recovery, drop contamination density and cumulative mass distribution. Keuffel and Esser Company Numbers 461510 and 46840 should satisfy most requirements. Finally, a desk-top programmable calculator is recommended for simple and rapid analysis of the numerical data developed from the card counting and sizing as described in Section 5.2. The 9820A Calculator manufactured by Hewlett-Packard, Loveland, Colorado, is ideally suited for this purpose, since it allows alpha-numeric printout and identification of input parameters. Also, when used in conjunction with the 9862A Calculator Plotter, an automated plotting capability is provided. The use of a preprogrammed calculator greatly reduces the chances of human errors affecting the results and significantly reduces the time required to complete the analysis.

SECTION 3

# DESIGNING THE SAMPLING GRID; OPERATIONAL CONSIDERATIONS

Trials for determining the characteristics of small aircraft spray systems are best conducted with the aircraft flying at a low altitude and headed into the wind. The inwind flight trajectory ensures that the entire drop-size spectrum of the spray cloud can be sampled with a minimum number of samplers and also provides estimates of the minimum swath width that can be expected under operational conditions during the forest spray project. In this section, the design of a sampling network for measuring spray characteristics and suggestions for conducting the trials are described.

## 3.1 DESIGN OF THE SAMPLING GRID

### 3.1.1 Choosing The Site

Large cleared and relatively level areas are ideally required for determining spray characteristics. Buildings, trees, power lines, and other obstructions interfere with the placement of sampling lines, with the wind-flow field, and with the aircraft flight pattern. Since the card samplers are placed on the ground, high grass or bushes can intercept the drops before they reach the cards. For this reason, mowing or other means of removing large plant forms in the immediate vicinity of the sampling lines may be required. Irregularities in the ground surface can also act to confound the results of the trials and should be avoided where possible. The aircraft pilot must maintain level flight for some distance downwind of the sampling line as the aircraft approaches the sampling line and for even greater distances upwind of the sampling lines. The requisite length of the flight line depends, as will be discussed later, on the height of the aircraft. Aircraft heights of 50 to 100 feet require characterization sites exceeding one square mile in area. Sites where the public can easily gain access

should be avoided, since some of the dyed spray material could easily be deposited on people or cars within the spray area.

### 3.1.2 Grid Geometry

As noted above, an inwind flight trajectory ensures that the entire drop-size spectrum of the spray cloud can be sampled with a minimum number of samplers. The grid should be designed such that sampling lines are crosswind. Experienced meteorologists and test personnel know that specifying a mean wind-direction for a short-period averaging time well in advance of a trial is extremely difficult under the best of circumstances. Therefore, the sampling grid must be designed to accommodate variations in the mean wind direction to prevent the introduction of serious errors in the data analysis. For this reason, the equilateral triangle design shown in Figure 3-1 is recommended. Inspection of Figure 3-1 shows that this design tends to limit the angle between the aircraft flight path (flown into the wind) and a sampling line to 90 $\pm$ 30 degrees. Figure 3-2 shows the combinations of sampling lines and mean wind directions which would apply if north is assumed to be at the top of Figure 3-1. According to Figure 3-2, sampling line A can be used for all wind directions from 150 through 210 degrees and from 330 through 30 degrees. Sampling line B can be used for all winds from 30 through 90 degrees and from 210 through 270 degrees. Similarly, sampling line C can be used for all winds from 90 through 150 degrees and from 270 through 330 degrees. The choice of the proper flight path for any given trial is made, as explained in Section 3.2.3 below, from mean wind direction measurements made just prior to conduct of the trial.

Knowledge of the most frequent wind directions at the site chosen for the trials would assist in orienting the triangular design to further ensure that sampling lines are oriented crosswind. Spray projects are normally conducted during the early morning and late evening hours during periods of fair weather. The light wind conditions usually present during these hours are generally favorable for maximum

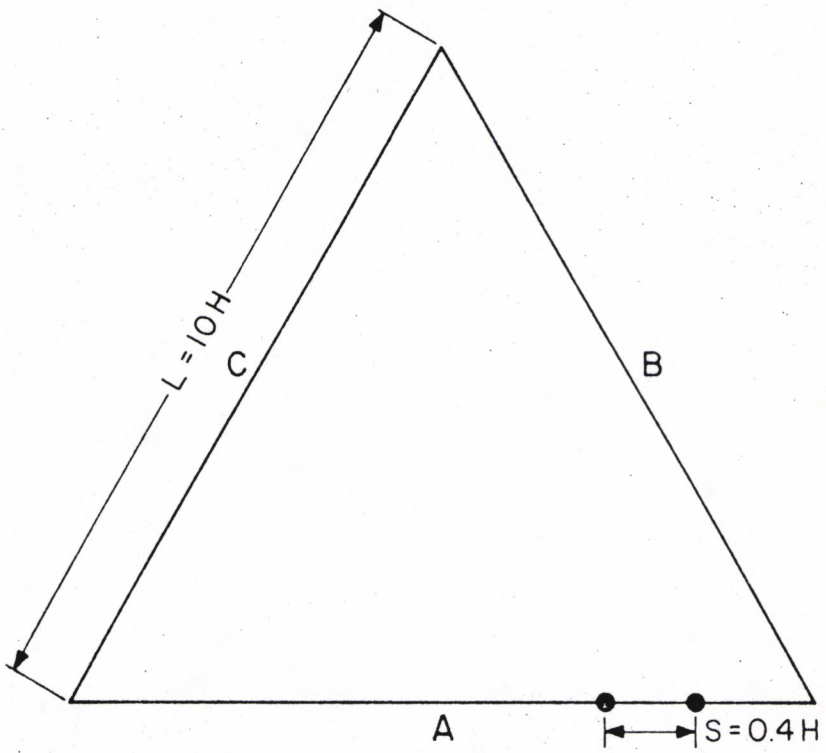



FIGURE 3-1. Simple equilateral triangle sampling grid for characterizing aircraft spray. The length of the sides L are 10 times the aircraft flight altitude H and the sampler spacing S is 0.4H.

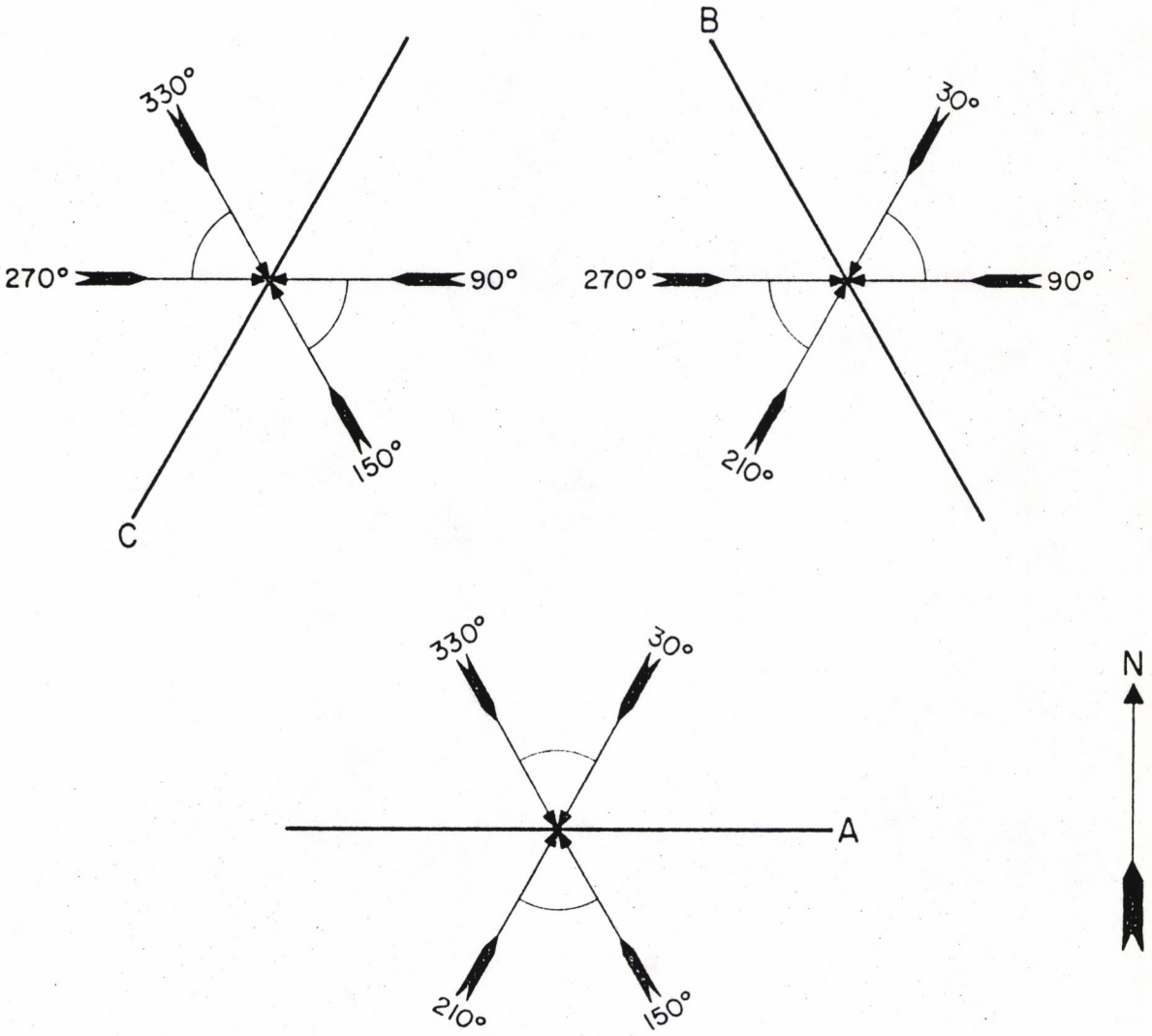



FIGURE 3-2. Illustration of the use of the sampling lines A, B and C of the basic grid design shown in Figure 3-1 with winds from various directions.

canopy penetration and minimum off-site drift of the spray material. Strong winds and high levels of atmospheric turbulence generally diminish spray deposition in the immediate target area and increase the possibility of downwind drift. The above considerations also apply to the determination of aircraft spray characteristics. Thus, one of the sampling lines should be oriented to be crosswind relative to the wind directions expected during the early morning or late evening hours. A trained micrometeorologist can often determine expected mean wind directions for these periods from a knowledge of the topographical features in the area.

## Length of the Triangular Sides

Each side of the triangular grid array must be long enough to contain the swath width or contamination density of interest. While rather complicated diffusion-deposition formulas can be used to determine the length L as a function of droplet settling velocity, height of the aircraft and meteorological conditions--experience has shown that the simple expression

$$L = 10H \tag{3-1}$$

where

L = length of side

H = aircraft height

normally guarantees the swath width will be contained. Thus, if the aircraft flies at a height of 15 meters (50 feet), the length of each side of the triangular array should be 150 meters (500 feet).

## Sampler Spacing

The sampler spacing along each side of the array must be sufficiently dense that statistically stable estimates of the volume median diameter and other spray

characteristics can be obtained. Again, modeling and field experience show that the expression

$$S = \frac{L}{25} = 0.4H \qquad (3\text{-}2)$$

where

S = maximum sampler separation distance

provides an adequate sampling array density. Thus, for an aircraft flight altitude of 15 meters (50 feet), the maximum distance between card samplers on the sampling line should be 6 meters (~20 feet).

### 3.1.2 Aircraft Height and Spray Line Length

For the purpose of characterizing aircraft spray, it is generally desirable that the aircraft fly as low as possible to minimize sampling grid requirements while satisfying flight safety requirements. Consideration must also be given to the operational requirements of the spray project for which the characterization is performed. If the project is to be conducted over rough terrain the aircraft may not be able to operate safely at altitudes lower than 30 meters (100 feet) above the canopy. In this case, the characterization trials should be conducted with an aircraft altitude of 30 meters above the ground. A 15-meter (50-foot) minimum altitude often meets both requirements of safety and grid design. The flight altitude may have to be increased, however, if the density of the stains from drops deposited on the sampling cards is so great that spray characteristics cannot be determined. Since the stain spread factor of drops depends on the type of material released by the aircraft, the type of sampling card and other spray characteristics that may not be known prior to the trials, it is difficult to recommend a specific aircraft altitude. A simple one-trial

experiment at an aircraft altitude of 15 meters can be conducted prior to final specification of the grid design to determine if the cards will be covered so heavily that stains cannot be counted and sized. On the other hand, a value for the length L of 300 meters can be used in the grid design for a 30-meter aircraft altitude with a sampler separation distance S of 6 meters appropriate for an aircraft altitude of 15 meters. If the first trials indicate that a 15-meter altitude results in spray densitites that cannot be conveniently counted, the flight altitude can be increased to 30 meters and every other sampling position removed from each side of the triangular grid. Since spray density is nearly inversely proportional to aircraft altitude, an increase in aircraft altitude by a factor of two will reduce deposition density by half.

The length of the inwind release line required to ensure that the crosswind mass recovery sampled on the grid is not affected also depends on the aircraft altitude as well as spray characteristics and meteorological conditions. Calculations show that if much of the spray cloud mass is comprised of drops with diameters of 50 micrometers or less and wind speeds are less than or equal to 4 meters per second, the length of the release line RL upwind of the sampling grid should be about one-hundred times the aircraft altitude, or

$$RL = 100H \qquad \{D \leq 50\,\mu m\} \tag{3-3}$$

If most of the mass of the spray cloud is comprised of drops between 50 and 100 micrometers in diameter and wind speeds are less than 4 meters per second, the length of the release line upwind of the sampling grid should be about seventy times the aircraft altitude, or

$$RL = 70H \qquad \{50 < D \leq 100\,\mu m\} \tag{3-4}$$

Finally, if most of the spray cloud mass is comprised of drops greater than 100 micrometers in diameter, the length of the release line upwind of the sampling grid need only be about thirty-five times the aircraft altitude, or

$$RL = 35\,H \qquad \{100\mu m < D\} \tag{3-5}$$

In every case, the release line must begin at least 50 to 100 meters downwind of the sampling grid. Longer distances may be required to stabilize the aircraft altitude and the flow rate in the spray dissemination system.

### 3.1.3 Summary of Grid Design Requirements

The sampling grid recommended for use in characterizing spray from small aircraft is shaped in the form of an equilateral triangle.

The length of each side of the triangle L is

$$L = 10\,H$$

where H is the planned aircraft flight altitude.

The maximum separation distance S between sampling cards placed along each side of the triangle is

$$S = 0.4\,H$$

The release line should extend upwind from the sampling line a distance RL given by

$$RL = \left\{ \begin{array}{l} 100\,H;\ D \leq 50\mu m \\ 70\,H;\ 50 < D \leq 100\mu m \\ 35\,H;\ 100\,\mu m < D \end{array} \right\}$$

where RL depends on the size of drops expected to be generated by the spray aircraft.

For example, assume the planned aircraft flight altitude for the spray characterization is 15 meters (50 feet) above the ground and most of the mass is expected to be contained in drops with diameters between 50 and 100 micrometers. The length of each side of the triangular grid should be

$$L = 10\,H = 10\ (15) = 150 \text{ meters } (\sim 500 \text{ feet})$$

The distance between sampling card positions along each side of the triangle should not be more than

$$S = 0.4\,H = 0.4\ (15) = 6 \text{ meters } (20 \text{ feet})$$

The inwind release line should extend upwind from the sampling line a distance

$$RL = 70\,H = 70\ (15) = 1050 \text{ meters } (3500 \text{ feet})$$

## 3.2 OPERATIONAL CONSIDERATIONS

### 3.2.1 Dressing The Grid

After the length of the triangular sides of the sampling grid and the sampler grid spacing have been determined, the transit or theodolite and the manilla rope are used to lay out the sampling lines. The manilla rope is stretched taut at right angles to the most probable wind direction expected during the early morning hours using the theodolite to ensure that the line segment is straight and correctly oriented. Quarter-inch stock metal rods are then driven or forced into the ground at the predetermined sampling intervals marked by the surveyor's tape tacked to the rope. The rope is then moved and the above procedures repeated until the sampling line length is long enough to form one side of the triangular grid array. The transit is then used to measure the 60-degree angles and lay out the next two sides of the array. Wood stakes, 5 to 6 feet high and marked with bright tape, should be placed at the end of each leg of the triangle and at the center position of each leg. It may be necessary to clear a small area around each metal rod so that plants or other material do not intercept drops that would otherwise impact on the card.

Cards for three or more trials can be premarked and placed in cardholders prior to each day's operation. At a minimum, the marks placed on each card should identify the trial (or flight) number, sampling line number, and sampler location on the line. For example, the identification 13-A-50 might indicate Trial 13, Sampling line A and the 50th-card position on sampling line A. The cards in their cardholders can be packed in ascending numerical order in the wooden boxes described in Section 2.1 for transportation to the field site such that one or two boxes, depending on the length of the sampling line, are sufficient to dress one side of the triangular array. The cardholders should be placed at the side of each stake so that the stake does not intercept drops which would otherwise strike the card. The cardholder must be placed flat on the ground and care must be taken that loose soil or dust is not kicked onto the card in placing the card or in picking up the samplers after the trials.

Because of the triangular grid array, not all cards on all sides of the array will be exposed during a single trial or aircraft pass over the grid. To avoid confusion in sample card designation, it is best to pick up all premarked cards on all sides of the array after each trial. Those cards obviously not exposed during the trial can be remarked later for use in trials at a later time. If cards on one side of the array are not exposed and left for the next trial, care must be taken to change their trial identification as they are picked up in subsequent trials and after they have been exposed to spray deposits.

### 3.2.2 Location and Operation of Meteorological Equipment

The low-level (2-meter) wind-direction and speed sensors and associated recording equipment are best located near the center of the triangular grid, well away from any of the sampling lines. Vehicles or other obstructions to wind flow should never be placed near the sensors when data are being recorded. Manufacturer's instructions must be carefully followed during the assembly and placement of the equipment to prevent damage. Special care must be taken in fitting the wind vane and speed assemblies into their sockets so that heavy thrust is not placed on the bearings of the drive. The bearing must always be checked for damage by checking for completely free rotation of the vanes.

In using the transit or theodolite to orient the wind vane, it must be remembered that wind direction is always recorded as the direction from which the wind is blowing. The orientation point should be in the direction of the most frequently-occurring wind. Select a nearby prominent landmark that can be seen in dim light and is not likely to be obscured by clouds or fog. If no landmark is convenient, drive a stake for use in sighting the vane. Align the transit or theodolite with the vane and orientation point and note the direction. Rotate the head of the wind vane, after loosening the alignment screw to permit free movement, until the recorder pen is making a trace at the center of the chart when the vane is pointing toward

the orientation point. Tighten the alignment screw and recheck the orientation. Repeat the process until the recorder pen is centered while the vane is pointed toward the orientation point. Note the direction of the orientation point on the chart. This procedure will have to be repeated if, during the trials or just prior to a trial, the wind direction is such that the recorder pen is moving back and forth from one edge of the chart to the other.

If possible, the wind equipment should be operated continuously during the period of the characterization trials and for several days prior to the trials. The continuous record is useful in determining wind-flow patterns to be expected during the early morning and evening hours when the trials are to be conducted. A chart speed of 3 inches per hour is adequate for continuous recording of the wind direction and speed, but the chart speed should be increased to a minimum of 12 inches per hour before the spray run of the aircraft and continued for a 10- to 15-minute period after the aircraft has completed the spray run. Since chart drives do not always operate accurately, the correct time should be entered opposite time "hacks" or marks on the chart at frequent intervals. The trial number, time and date of each trial must be indicated in the margins of the chart. Any significant weather phenomena or changes in instrumentation (reorientation) should also be noted directly on the charts.

The operation of a tethersonde and release of pilot balloons for measuring vertical wind and temperature structure during the conduct of characterization trials are optional. An experienced meteorologist can make use of these observations in predicting the times for onset of favorable winds. If the trials are being conducted for research purposes, the vertical meteorological data are essential for documenting trial conditions. It is beyond the scope of this manual to explain the use of this information in the conduct and detailed analysis of spray trials. If at all possible, the measurements should be made and included in the documentary support of the trials. The tethersonde base station location and point where pilot balloons are released should be located as near as possible to the sampling grid array without

causing interference with aircraft operations. Manufacturer's instructions for operating the tethersonde must be carefully followed, especially those for calibration of the equipment. Instructions for making pilot balloon measurements and reducing the observations to obtain wind directions and speeds are contained in the publication "Winds Aloft Observations Manual, Handbook No. 5" published by the National Oceanic and Atmospheric Administration (NOAA) and available from the U. S. Government Printing Office. It should be noted that accessory equipment for operation and analysis of the tethersonde and pilot balloon data are not included in the equipment lists given in Section 2.

### 3.2.3 Conducting the Trial

Spray characterization trials are best conducted under reasonably steady-state meteorological conditions. Large changes in wind direction can result in shifts in the spray cloud pattern which serve to confound the determination of the effective swath width and deposition efficiency. The best spray deposition patterns are usually obtained during the early-morning and late-evening hours when the wind speeds are low and the thermal stratification is neutral. However, meteorological conditions during these hours are typically unsteady. The procedures described below are suggested as the most effective means of ensuring that conditions are sufficiently steady for the conduct of spray characterization trials.

Operate the 2-meter wind recording equipment at a chart speed of 12 inches per hour for at least 1 hour prior to the trials. For the two most recent 10-minute periods, lightly draw two straight lines, each 2 inches long (equivalent to 10 minutes of chart record) through the recorded wind direction data to obtain estimates of the mean wind direction during each of the 10-minute periods. If the two 10-minute mean wind directions do not differ by more than 15 degrees, the wind direction is sufficiently steady for conducting a trial. Draw similar lines through the two most recent 10-minute periods of wind speed. If both of the 10-minute average wind speeds fall within the limits of 1.5 to 4 meters per second (3.5 to 9 miles per hour), wind speed

conditions are favorable for conducting a trial. Release a smoke grenade and observe the vertical spread or diffusion of the smoke. In the very early morning or very late in the evening when wind speeds are light, the smoke may not spread vertically with distance to the height of the planned aircraft altitude. If the smoke "hugs" the ground with little vertical spreading as shown in Figure 3-3(a) indicating a very stable thermal stratification of the atmosphere, delay the trials. In the late morning or in the afternoon, the smoke may lift quickly from the ground as shown in Figure 3-3(b), may form loops alternately lifting from and intersecting with the ground, or diffuse too rapidly. Under these conditions, the atmosphere is too unstable and spray characterization trials should be delayed. If the smoke plume grows regularly in the vertical with increasing downwind distance as shown in Figure 3-3(c) and reaches the aircraft altitude at a reasonable distance from the source (a distance equal to about 10 H), diffusion conditions are suitable for characterization trials. If the wind direction and speed criteria outlined above are also satisfied, the trials should be conducted.

Two persons are required to be present on the sampling grid during the trial, one to monitor the 2-meter wind equipment and the other to release a smoke grenade and communicate with the aircraft pilot. When the grid is cleared, the aircraft is airborne, and the meteorological conditions are satisfactory, a second smoke grenade should be released at the center stake of the triangular side of the sampling array facing the wind to serve as a guide to the aircraft pilot. The pilot maintains the correct altitude, aligns his aircraft with the smoke plume and flies upwind towards the source of the smoke. The spray dissemination equipment should be turned on at a distance downwind from the smoke source that allows the flow rate to become stabilized. Dissemination is then continued past the sampling grid for a distance corresponding to the precalculated length of the release line RL discussed in Section 3.1.2 above. The person monitoring the wind equipment should mark each chart to indicate the points on the chart corresponding to the time the aircraft passes over the sampling line, and the time. Other information, such as the trial number,

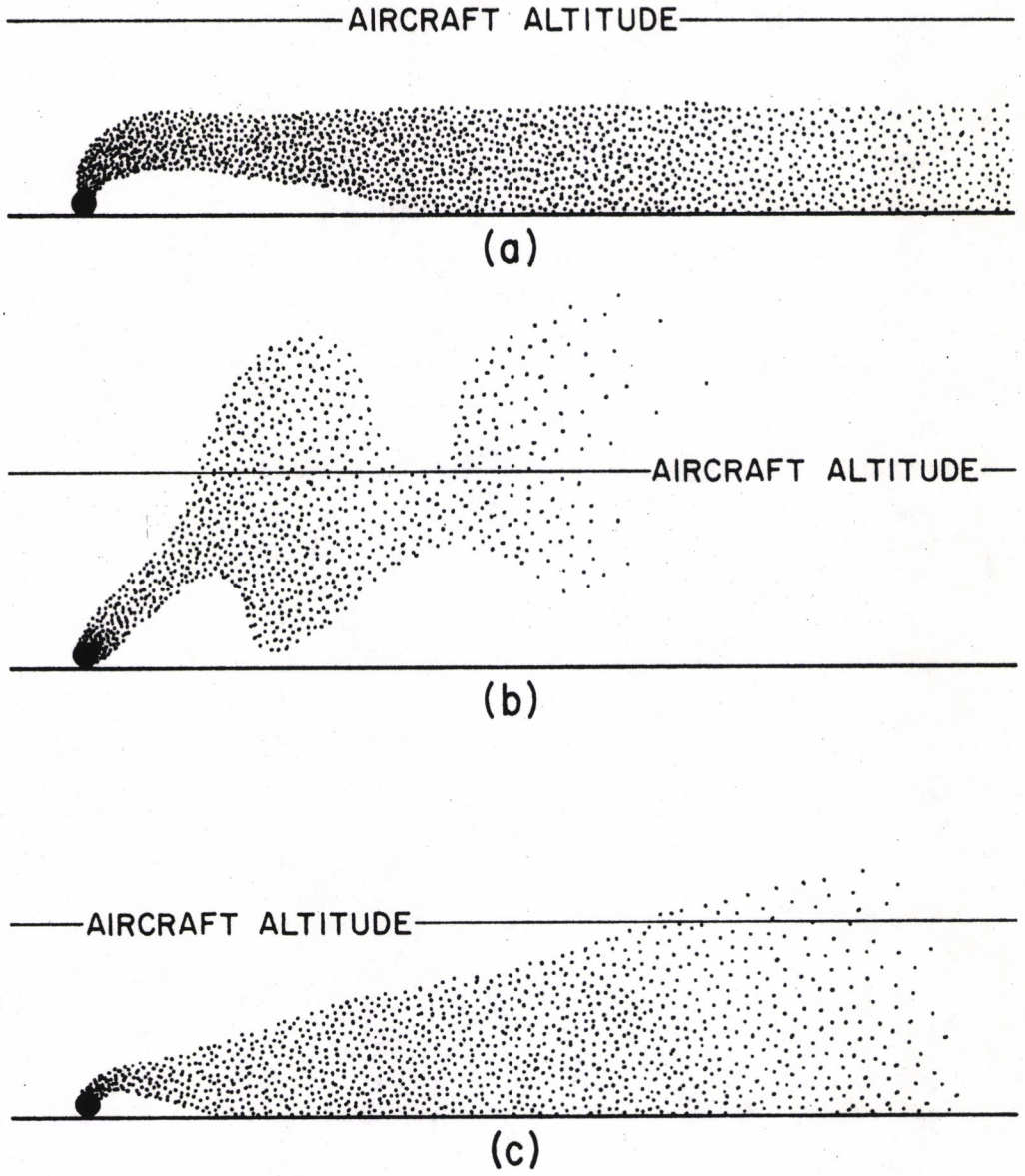



FIGURE 3-3. Schematic diagram showing smoke plume diffusion under (a) conditions too stable for characterization trials, (b) conditions too unstable for characterization trials and (c) favorable conditions for spray characterization trials.

time duration of the trial, sky cover, observations of the spray-cloud behavior and other observations pertinent to the conduct of the trial should also be noted.

After the spray cloud has settled and the droplets have dried on the cards, preparations for the field characterization of the spray trial, discussed in Section 5 below, can be made.

### 3.2.4 Trial Log

An example form for recording pertinent information regarding the spray system and meteorological data for each trial is shown in Figure 3-4. Many of the items can be completed in the field prior to and just after the trial has been conducted. The analysis of the pilot balloon and tethersonde data to obtain vertical profiles of wind and temperature data may take several hours or days to complete and can be entered later. Nozzle spacing on aircraft booms is often nonuniform and nozzles may or may not be located beneath the aircraft body. Note that space has been provided in Section III of the Trial Log for use in sketching the nozzle spacing and configuration used in the trial.

FIGURE 3-4

TRIAL LOG

Trial Number _____ Time/Date _____ Time Zone _____

Row _____ Row Azimuth _____ o Card Separation _____ m

Number of Cards _____

I. SPRAY SYSTEM DATA

Aircraft _____

Spray Nozzle _____ Nozzle Orientation _____

Airspeed _____ (mph) Flow Rate _____ gallons $min^{-1}$

Flight Altitude _____ (ft or m ) Aircraft Heading _____ o

Spray Material _____ Material Density _____ g $cm^{-3}$

Stain Factor Formula _____

Stain Factor Constants _____ _____ _____

II. METEOROLOGICAL DATA

Cloud Cover _____ % Temperature _____ $^oC$

2-m Wind Direction _____ o 2-m Wind Speed _____ m $sec^{-1}$

Relative Humidity _____ %

(Optional Measurements Using Pilot Ballons and/or Tethersonde)

Wind Profile

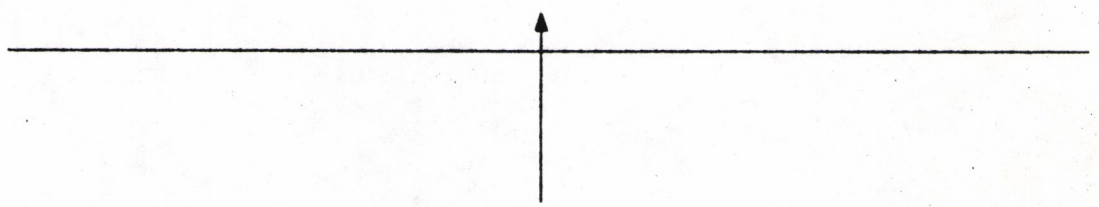
| Height (m) | Direction ($^o$) | Speed (m $sec^{-1}$) |
|---|---|---|
| | | |

Temperature Profile

| Height (m) | Temperature ($^oC$) |
|---|---|
| | |

FIGURE 3-4 (Continued)

III. NOZZLE CONFIGURATION




IV. REMARKS

# SECTION 4

# FIELD CHARACTERIZATION OF THE SPRAY DISSEMINATION SYSTEM

The procedures described below for determining swath width, drop density within the swath and volume-median diameter are designed to provide in-the-field characterization of the aircraft spray. For example, these "quick-look" procedures are intended to provide aircraft spray engineers with the information required to make immediate decisions regarding necessary changes in nozzle types, nozzle configurations, flow rate and to make other mechanical adjustments in the dissemination system to improve spray characteristics. These procedures are also intended for use in determining any changes required in the aircraft flight altitude, separation distance of the card samplers and other features of the test plan to achieve better results. Final characterization of the aircraft spray system requires a more complete data analysis which is described in Section 5.

## 4.1 PLASTIC TEMPLATES FOR SIZING AND COUNTING DROPS

The analysis procedures described here and in Section 5 require the use of clear plastic templates to overlay the exposed sample cards. Sample templates are attached to this manual. Since continued use of the templates will eventually result in their becoming scratched and unusable, it is necessary to provide replacements. This can best be accomplished by having a draftsman draw the templates on tracing paper at three times the size shown in the figures using a No. 0000 Leroy pen. This original drawing is then photographed, reduced 33.3 percent and then reproduced on clear 4 mil mylar film. The negative produced in this process can be used over and over to make new templates as required.

## 4.2 SWATH WIDTH AND DROP DENSITY

The spray project entomologist is interested in obtaining the widest swath width in which droplet density exceeds a specified amount known or thought to produce

the requisite pesticide effectiveness. A "quick-look" estimate of the minimum swath width and drop density within the swath width can be obtained by following the simple procedures described below.

After the visible spray cloud has settled or dispersed, proceed on foot from one end of the exposed card line until spray deposition on the sampling cards becomes visible to the naked eye. Visually inspect the next few cards and note the position of the first card on which the drop density appears to be uniform. After inspecting this card to be certain that the stains have dried, estimate the spray drop density on this card using the following step-wise procedure:

(1) Remove the card from its holder.

(2) Place the template shown in Figure 4-1 over the card and fasten the card and template to the clipboard.

(3) Use the large hand-held magnifying glass to count the number of stains in the small (1 square centimeter) square in the upper left-hand corner. Note the number of stains on scratch paper.

(4) Continue to the next square moving down the extreme left column of squares on the template. Count the stains in the square and add the number to the number of stains determined for the first square (step 3). If the total number of stains exceeds 100, no more squares need be counted. If the total number of stains is 100 or less, continue to count the stains in squares until the total number of stains exceeds 100 for all squares counted.

(5) Enter the card number, total number of squares counted (area in square centimeters) and total number of stains in the columns provided in the field information sheet shown in Figure 4-2.

(6) Divide the number of stains by the area and enter the drop density in the last column of Figure 4-2.

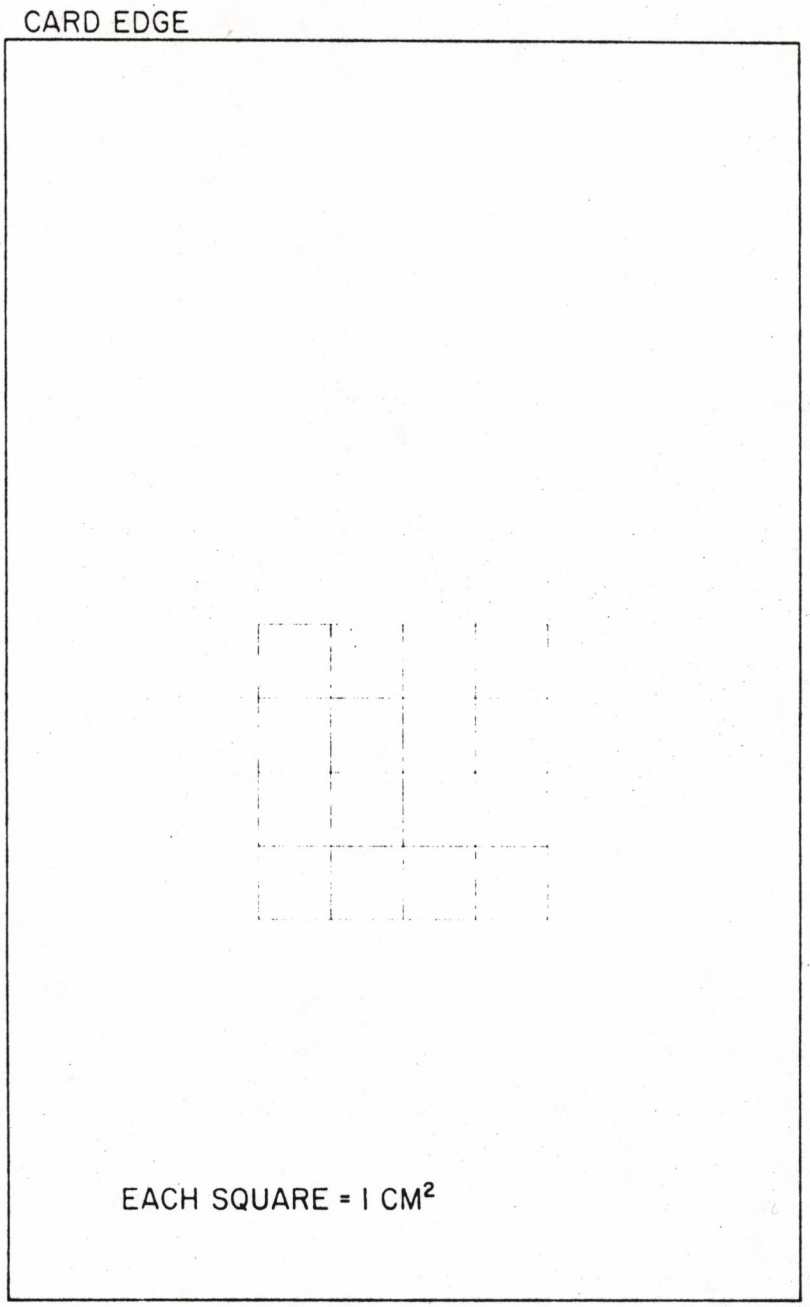



FIGURE 4-1. Template for counting of drops on sampler cards in the field.

FIGURE 4-2

FIELD ESTIMATE OF SWATH WIDTH AND DROPLET DENSITIES

Date _____
Trial Number _____
Row/Line Number _____

| Card Number | Area ($cm^2$) | No. of Stains | Density (drops $cm^{-2}$) |
|---|---|---|---|
| _____ | | | |
| _____ | | | |
| _____ | | | |
| _____ | | | |
| _____ | | | |
| _____ | | | |
| _____ | | | |
| _____ | | | |

Card Number for Left Edge of Swath _____

Right Edge of Swath _____

Estimated Swath Width _____

(7) Replace the card in its cardholder and return the cardholder to its original position for later pickup.

If the drop density on this first card is less than the density required to produce the requisite pesticide effectiveness, use the density just measured as a guide and walk along the card line towards cards showing greater densities and attempt visually to select a card showing the requisite density. For example, if the first card shows a density of 10 drops per square centimeter and the required density is 20 drops per square centimeter, proceed along the card line and select a card showing twice the density of the card just measured. Follow the same procedure for counting the stains to obtain drop density. If the measured drop density on the selected card is greater than or approximately equal to the required density, the edge of the swath can be obtained by linear interpolation. As soon as this edge of the swath is defined, walk to the other end of the card line and use the same procedures to define the other edge of the swath.

After defining the swath width, use the procedures for counting stains outlined above to estimate the drop density of the card near the swath center visually indicating the greatest density. Estimate the drop density on at least two other cards. If the drop density distribution along the card line is uniform or Gaussian (bell-shaped), select a card half-way between the swath end and swath center on either side of the card showing the greatest density. If the distribution is slightly asymmetrical, which can occur when the aircraft does not fly directly into the mean wind, select the additional cards for analysis from the side of the distribution with the longest "tail." When the distribution appears highly assymmetrical, an additional trial must be conducted to estimate the minimum swath width. After the drop-density estimates have been completed, enter the position numbers of the cards marking the swath edges at the bottom of the form shown in Figure 4-2; subtract the position numbers and multiply by the sampler separation distance to obtain the estimated swath width. Enter the swath width on the form.

The analysis of drop density on 5 cards is usually more than sufficient to define the swath width for field use and provide the necessary information to allow aircraft engineers to make necessary adjustments in spray equipment and assist the project entomologist in making a preliminary estimate of the spray system performance. In many cases, measurement of the drop density at the swath edges may provide sufficient information in the field. More complete information will be available after the field laboratory analysis is completed (see Section 5).

It should be noted that the drop density analysis and the volume median diameter analysis described in Section 4.3 below are best accomplished using two people, one to count the drops and the other to record the information.

## 4.3 FIELD ESTIMATION OF VOLUME MEDIAN DIAMETER

The procedures outlined in this section for the field estimation of the volume median diameter (VMD) are based on the approach suggested by B. Maksymiuk (1964). Although Maksymiuk tested his approach using propeller-driven slow and medium speed aircraft and oil-based sprays, recent experience in applying the method with helicopter equipment and oil- and water-based sprays indicates the method is also adequate for the field estimation of VMD's for this type of equipment and sprays.

In the following discussion, it has been assumed that the "stain factor" has been measured prior to the trials. The stain factor is the relationship between the drop size before impaction on the sampling card and the size of the stain produced by the drop on the card. A typical relationship is given by the expression

$$DD = a + b\,(SD) + c\,(SD)^2 \qquad (4\text{-}1)$$

where

DD = drop diameter

SD = stain diameter

and a, b, and c are constants determined in the laboratory. In the above expression there is no specific provision for the spread of the stain as a function of time after the drop impacts. For some oil-based sprays and some types of sampling cards, the stain can continue to spread for hours after drop impact. When long periods of time are required for stabilization of stain diameters, the analysis of VMD (and perhaps drop density estimation) must either be delayed until stabilization occurs or the time after drop impact be included in the stain factor expression. Also, in the case of long stabilization times, cards may either have to be left on the sampling grid for longer times or special care taken to protect the cards during collection from the grid to prevent smudging.

The D-max method for estimating VMD is based on inspection of sampling cards for large diameter stains. In theory, use of the method requires selecting and measuring the largest stain on every card along the sampling line before selecting the five largest drops. In practice, the larger diameter stains usually occur near the center of the swath on the cards which also exhibit the highest drop densities, thus simplifying the estimation procedure. The following procedure is recommended.

(1) Select the sampling card near the center of the swath exhibiting the highest drop density.

(2) Visually inspect the card and select the largest stain appearing on the card.

(3) Measure the stain diameter to the nearest 50 micrometers using the measuring magnifier graduated in 100 micrometer intervals.

(4) If there are several stains nearly as large as the largest stain on the card, measure their diameters.

(5) Enter the card number and stain diameter(s) on the form shown in Figure 4-3.

(6) Proceed to the next card to the left (right) and repeat the measurement procedure.

(7) Continue measuring the largest stains on cards to the left (right) of the swath center until it becomes obvious that additional cards could not yield one of the five largest drops.

(8) Repeat the measurement process on the right (left) side of the swath center.

(9) Using the stain factor, compute the drop diameter for the largest stains on each card, and enter the results on the form shown in Figure 4-3. A battery-operated pocket calculator is recommended for use in making this calculation.

(10) Select the five largest drop diameters from the tabulated values and enter their card numbers and diameters in the spaces provided on the right-hand side of the form; enter the largest diameter at the top and the smallest diameter at the bottom. If two or more drops are of the same size, they should still be counted as separate drops and listed sequentially in the "Five Largest Drops" table.

(11) The largest drop appearing in the "Five Largest Drops" table is used in the next step to estimate the VMD for the trial, providing that the difference in diameter between any two successively ordered drops does not exceed 32

FIGURE 4-3

FIELD CHARACTERIZATION OF VOLUME MEDIAN DIAMETER (VMD)

Trial Number _____

Time/Date _____

Row/Line Number _____

Aircraft _____

Aircraft Altitude _____

Aircraft Speed _____

Spray Material _____

Flow Rate _____

Miscellaneous _____

_____

_____

Stain Factor Constants a _____

b _____

c _____

Stain Factor Relationship:

$DD = a + b(SD) + c(SD)^2$

DD = Drop Diameter

SD = Stain Diameter

Largest Stains and Drops

| Card Number | Stain Diameter | Drop Diameter |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Five Largest Drops

| Card Number | Drop Diameter |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |

$$VMD = \begin{cases} DD/2.2 & (80\text{–}120 \text{ mph}) \\ DD/2.5 & (> 120 \text{ mph}) \end{cases}$$

VMD = _____

micrometers. If a difference in diameter greater than 32 micrometers occurs between any of the drops, the drop just below the 32-micrometer gap is used in the next step.

(12) The VMD for the trial is estimated by dividing the drop selected in Step (11) by a factor of either 2.2 or 2.5, depending on the speed of the aircraft as noted in the form. Enter the VMD in the space provided.

As mentioned above, two formulas are shown on the form in Figure 4-3 for calculating VMD. If the aircraft speed during the trial was between 80 and 120 miles per hour, the largest drop diameter DD is divided by the conversion factor 2.2. If the speed was greater than 120 miles per hour, DD is divided by 2.5. These conversion factors (2.2 and 2.5) are somewhat arbitrary. Maksymiuk (1964) established that the factors were dependent on aircraft speed. However, in the trials used to develop the technique, the aircraft flew at 80 miles per hour and at 170 miles per hour, resulting in the definition of the two factors shown in the table. Since a more definitive estimate of VMD will be obtained in the field laboratory analysis described in Section 5 below, it may be possible to obtain refined estimates of the conversion factors for use in subsequent trials. As an example of the application of the D-max technique, assume that the aircraft speed was 90 miles per hour and the five largest drops diameters measured on the cards in ascending order were 263, 286, 286, 321 and 335 micrometers. The VMD for the trial is calculated as follows:

$$\text{VMD} = \frac{286}{2.2} = 130 \text{ micrometers}$$

After completion of the procedure for estimating VMD, the field crew can collect the cards and prepare the sampling grid for the next trial.

SECTION 5

# FIELD LABORATORY CHARACTERIZATION OF THE AIRCRAFT SPRAY DISSEMINATION SYSTEM

Field laboratory procedures for determining the swath width from drop density counts, evaluating the drop-size distribution within the swath width to obtain the volume median, average mass and number median diameters, and the mass recovery and deposition efficiency within the swath are described below.

## 5.1 DROP DENSITY DISTRIBUTION IN THE SWATH

The field laboratory procedures for estimating the drop density on sampling cards are similar to those described in Section 4.2 above. In the laboratory, however, drop densities are estimated for all cards within the swath and more drops are counted on each card to improve accuracy. In addition to defining the drop density distribution in more detail, the distribution is used (see Section 5.3) to calculate mass recovery within the swath.

The first step is to select the sampling cards to be analyzed. Using the results obtained from preliminary counts made in the field (see Figure 4-2), select the card on each edge of the swath that shows a drop density below the density producing the requisite pesticide effectiveness. If this cannot be done from the preliminary data entered on the form shown in Figure 4-2, it may be necessary to count some cards near the swath edge to redefine the swath width before proceeding to determine the drop densities on all cards within the swath.

For counting and sizing drops in the field laboratory, the template illustrated in Figure 5-1 and the measuring magnifier are used to count the drops. The 4, 8, and 16 square-centimeter areas are arranged on the template so that the top of the area to be counted is at the center of the card when the line at the top of the template labeled

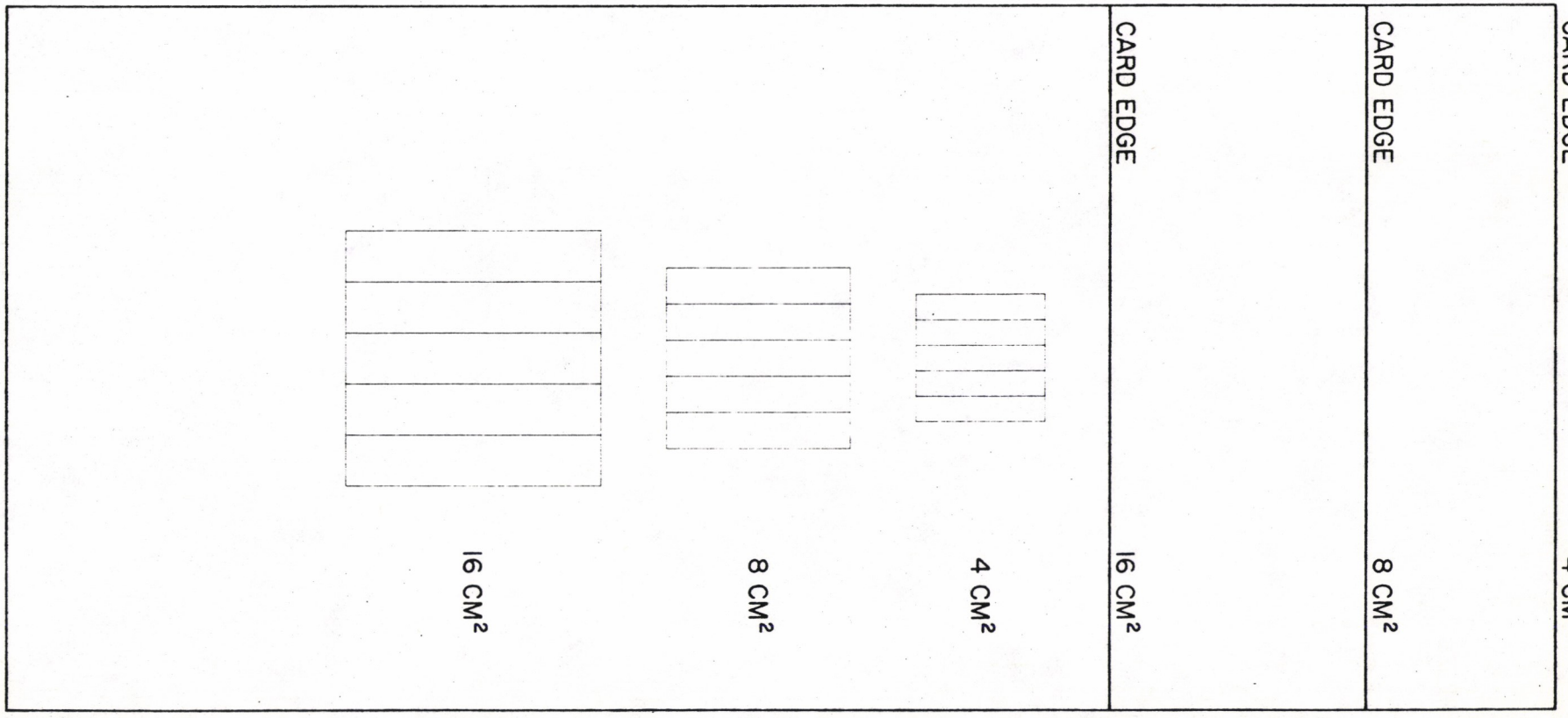



FIGURE 5-1. Template for counting and sizing drops on sampler cards in the field laboratory.

with the corresponding area is aligned with the top of the sampling card. In the counting procedure, the whole area (4, 8 or 16 square centimeters) will be counted. Select an area which will result in at least 200 drops being counted. With a little experience, one can usually readily select the proper area to be counted by visual inspection of the card. After this selection has been made, the area to be counted should be examined for obvious anomalies that might affect the accuracy of the count. These anomalies include smeared drops, foreign matter on the card or shadows (absence of drops) where deposition has been prevented by a leaf or some other object. If anomalies occur, move the template to an unaffected portion of the card. Once an anomaly-free area has been found, anchor the template and card to the cork board with push pins. The results of the drop density count are recorded on the Drop Density and Mass Deposition Data Sheet shown in Figure 5-2. Record the trial number, row/line number and card number, and area being used for counting on this data sheet.

When the measuring magnifier suggested for use in Section 2 is employed, stains less than 50 micrometers ($\mu$m) in diameter should not be counted. If drops with stains less than 50 $\mu$m are important in determining mass recovery (i.e., more than 5 percent of the mass distribution is comprised of drops with stain diameters less than 50 $\mu$m in diameter), a more precise instrument is required to count and measure the stains. As a general rule, drops with diameters a factor of three less than the volume median diameter (VMD) estimated in the field do not greatly contribute to mass recovery. Thus, if the relationship between stain and drop diameter is given by an expression similar to Equation (4-1), the critical stain diameter can be calculated from

$$CD = \frac{VMD}{3b} - \frac{a}{b} \qquad (5\text{-}1)$$

FIGURE 5-2

DROP DENSITY AND MASS DEPOSITION DATA

Trial Number _____ Average Mass Diameter _____ ($\mu$m)

Row Number _____ Mass _____ (mg)

Conversion Factor: 1 oz. acre$^{-1}$ = 1.427 x 10$^{3}$ mg cm$^{-2}$

| Card Number | Template Area (cm$^2$) | Stain Count | Drop Density (drops cm$^{-2}$) | Deposition | |
|---|---|---|---|---|---|
| | | | | (mg cm$^{-2}$) | (oz. acre$^{-1}$) |
| | | | | | |
| Total | | | | | |

Mass Recovery _____ (mg m$^{-1}$)

Deposition Efficiency _____ (percent)

where

CD = critical stain diameter

VMD = volume median diameter estimated in the field for a given trial

a, b = constants from stain factor determination given in Equation (4-1)

If the value obtained for CD is less than 50 $\mu$m, then a more precise instrument than the Bausch and Lomb measuring magnifier is required to count and size stains.

The template areas in Figure 5-1 are divided into five columns to assist in counting the drops. Each column is counted using the measuring magnifier and the total number of drops for each column is noted on scratch paper. Stains that intersect the outer perimeter of the template area should be included in the count only if more than one-half of the area covered by a stain is inside the perimeter line. Stains that intersect the lines dividing the area into columns must be counted in only one column, usually by assigning them to the column at the left of the line no matter how much of the stain is contained in a column. After all five columns are counted, the results are summed and entered in the "Stain Count" column in Figure 5-2. Calculate the drop density by dividing the stain count by the template area used and enter the result in the "Drop Density" column provided in the Figure. Count all cards included in the swath width. The columns labeled "Deposition" in Figure 5-2 will be completed after calculating the average mass diameter in Section 5.2 below.

## 5.2 DETERMINATION OF THE SWATH DROP-SIZE DISTRIBUTION, MASS MEDIAN, AVERAGE MASS AND NUMBER MEAN DIAMETERS

The mass median, average mass and number median diameters are determined from the drop-size distribution for the swath. Experience has shown that the

drop spectrum analysis of 5 cards within the swath width is normally sufficient to estimate these parameters within 15 percent of the values that would have been obtained if all cards within the swath had been analyzed. The error is frequently less than 5 percent. The 5 cards for analysis are selected by using 1 card from each end of the swath, 1 card near the swath center and 1 card on each side of the center card located approximately half the distance between the end and center cards.

Before the drops are counted and sized, the drop-size categories must be specified.

## Selection of Drop-Size Categories

Normally, 8 to 10 drop-size categories are sufficient to adequately define the drop spectrum. The upper and lower limits of the stain size intervals must be determined before the stains are counted and sized. The following step-wise procedure for selecting the limits of the stain size intervals is suggested:

(1) Draw the line defining the relationship between stain and drop diameter on linear graph paper as shown in Figure 5-3, using Equation 4-1; in Figure 5-3, $a = 7.68$, $b = .199$ and $c = 5.73 \times 10^{-6}$. The curve should extend from the smallest-diameter stain to the largest-diameter stain counted in the "quick-look" field analysis.

(2) Mark the position on the curve of the stain VMD estimated in the "quick-look" field analysis by the D-max method. For example, the point marked + in Figure 5-3 corresponds to a VMD stain diameter of 600 $\mu$m or a drop diameter of 130 $\mu$m.

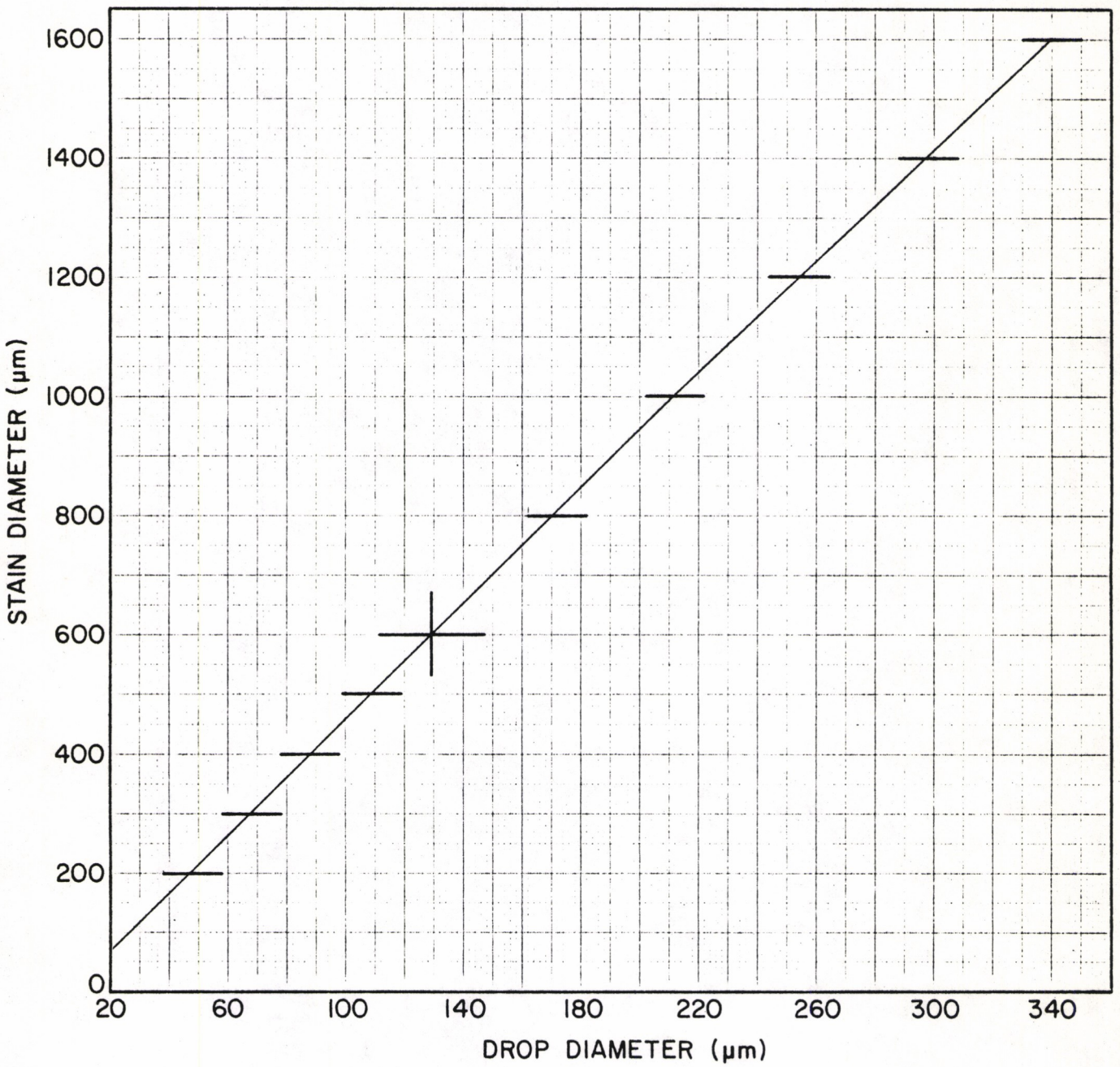



FIGURE 5-3. Stain factor relationship for example trial data. The + symbol is the stain VMD obtained from the "quick-look" D-max field analysis.

(3) Divide the line in Figure 5-3 into about five class intervals below the point marked + using standard intervals of 50 $\mu$m, 100 $\mu$m or multiples of 50 $\mu$m. The measuring magnifier is not accurate if the class intervals are less than 50 $\mu$m. For the example shown in Figure 5-3, the upper limits of the stain class intervals become 100, 200, 300, 400, 500 and 600 $\mu$m as shown by the short horizontal lines. The lower limit of the smallest class interval should correspond to the smallest drop counted in the spray deposit density count.

(4) Divide the line in Figure 5-3 above the point marked + into five intervals using standard stain intervals of 50 $\mu$m or 100 $\mu$m or other multiples of 50 $\mu$m. In the example shown in Figure 5-3, this procedure results in stain category upper limits of 800, 1000, 1200, 1400 and 1600 $\mu$m. If the VMD estimated by the D-max method is less than 100 micrometers, it may be necessary to divide the straight line above the point marked + into more than five intervals to obtain a representative mass distribution.

It should be noted that the basic graph shown in Figure 5-3 can be generated before the trials. Enter the stain class intervals on the Drop Spectra Data sheet shown in Figure 5-4 and use the stain factor equation relationship given by Equation (4-1) to convert the stain upper limits to drop-size upper limits. Enter the drop-size upper limits on the Drop Spectra Data sheet.

Having determined the drop-size categories, the drops on the cards can now be counted and sized. The template shown in Figure 5-1 is also used in making the

FIGURE 5-4

DROP SPECTRA DATA

Test 9 Row/Line C Spray Material DYLOX Material Density 1.067 ($g\ cm^{-3}$)

Analyst: John Doe Stain Factors: a = 7.68, b = 0.199, c = $5.73 \times 10^{-6}$

| | | Size Category | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Total |
| Stain Upper Limit ($\mu$m) | | 100 | 200 | 300 | 400 | 500 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | | |
| Stain Lower Limit ($\mu$m) | | 50 | 100 | 200 | 300 | 400 | 500 | 600 | 800 | 1000 | 1200 | 1400 | | |
| Drop Upper Limit ($\mu$m) | | 27.6 | 47.7 | 67.9 | 88.2 | 109 | 129 | 171 | 212 | 255 | 298 | 341 | | |
| Drop Lower Limit ($\mu$m) | | 17.6 | 27.6 | 47.7 | 67.9 | 88.2 | 109 | 129 | 171 | 212 | 255 | 298 | | |
| CARD NO. 43 TEMPLATE AREA 16 $cm^2$ | NUMBER OF DROPS | 41 | 118 | 121 | 85 | 85 | 40 | 45 | 7 | 2 | 1 | 0 | | 545 |
| | DROP DENSITY (drops $cm^{-2}$) | 2.562 | 7.375 | 7.562 | 5.312 | 5.312 | 2.500 | 2.812 | 0.4375 | 0.1250 | 0.0625 | 0 | | 34.06 |
| CARD NO. 46 TEMPLATE AREA 8 $cm^2$ | NUMBER OF DROPS | 44 | 83 | 54 | 21 | 21 | 11 | 5 | 3 | 1 | 0 | 0 | | 243 |
| | DROP DENSITY (drops $cm^{-2}$) | 5.500 | 10.380 | 6.750 | 2.625 | 2.625 | 1.375 | 0.6250 | 0.3750 | 0.1250 | 0 | 0 | | 30.38 |
| CARD NO. 50 TEMPLATE AREA 8 $cm^2$ | NUMBER OF DROPS | 69 | 91 | 60 | 24 | 14 | 5 | 2 | 1 | 0 | 0 | 1 | | 267 |
| | DROP DENSITY (drops $cm^{-2}$) | 8.625 | 11.38 | 7.500 | 3.000 | 1.750 | 0.6250 | 0.2500 | 0.1250 | 0 | 0 | 0.1250 | | 33.38 |
| CARD NO. 54 TEMPLATE AREA 8 $cm^2$ | NUMBER OF DROPS | 44 | 105 | 84 | 35 | 25 | 19 | 5 | 1 | 0 | 0 | 0 | | 318 |
| | DROP DENSITY (drops $cm^{-2}$) | 5.500 | 13.12 | 10.50 | 4.375 | 3.125 | 2.375 | 0.6250 | 0.1250 | 0 | 0 | 0 | | 39.74 |

FIGURE 5-4 (Continued)

| | | Size Category | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Total |
| CARD NO. 57 TEMPLATE AREA 8 $cm^2$ | NUMBER OF DROPS | 8 | 21 | 36 | 26 | 43 | 39 | 20 | 9 | 3 | 0 | 0 | | 205 |
| | DROP DENSITY (drops $cm^{-2}$) | 1.000 | 2.625 | 4.500 | 3.250 | 5.375 | 4.875 | 2.500 | 1.125 | 0.375 | 0 | 0 | | 25.625 |
| CARD NO. TEMPLATE AREA _____ $cm^2$ | NUMBER OF DROPS | | | | | | | | | | | | | |
| | DROP DENSITY (drops $cm^{-2}$) | | | | | | | | | | | | | |
| A | Mean Drop Diameter ($\mu$m) | 23.0 | 38.5 | 58.4 | 78.5 | 99.0 | 119.3 | 151.0 | 192.2 | 234.2 | 277.1 | 320.0 | | |
| B | Mean Drop Mass (mg) | $6.796 \times 10^{-6}$ | $3.188 \times 10^{-5}$ | $1.113 \times 10^{-4}$ | $2.703 \times 10^{-4}$ | $5.421 \times 10^{-4}$ | $9.486 \times 10^{-4}$ | $1.924 \times 10^{-3}$ | $3.967 \times 10^{-3}$ | $7.117 \times 10^{-3}$ | $1.189 \times 10^{-2}$ | $1.831 \times 10^{-2}$ | | |
| C | Sum of Drop Densities by Size Category | 23.19 | 44.88 | 36.81 | 18.56 | 18.19 | 11.75 | 6.812 | 2.188 | 0.625 | 0.0625 | 0.125 | | |
| D | Average Drop Densities by Size Category (drops $cm^{-2}$) | 4.638 | 8.976 | 7.362 | 3.712 | 3.637 | 2.350 | 1.362 | 0.4375 | 0.1250 | 0.00125 | 0.025 | | |
| E | Cumulative Drop Densities | 4.638 | 13.61 | 20.98 | 24.69 | 28.33 | 30.68 | 32.04 | 32.48 | 32.60 | 32.61 | 32.64 | | 32.64 |
| F | Cumulative Percent of Drop Densities | 14.21 | 41.70 | 64.28 | 75.65 | 86.80 | 94.00 | 98.17 | 99.52 | 99.88 | 99.91 | 100 | | |
| G | Average Deposition by Size Category (mg $cm^{-2}$) | $3.152 \times 10^{-5}$ | $2.862 \times 10^{-4}$ | $8.194 \times 10^{-4}$ | $1.003 \times 10^{-3}$ | $1.972 \times 10^{-3}$ | $2.229 \times 10^{-3}$ | $2.620 \times 10^{-3}$ | $1.736 \times 10^{-3}$ | $8.971 \times 10^{-4}$ | $1.486 \times 10^{-5}$ | $4.518 \times 10^{-4}$ | | |
| H | Cumulative Mass (mg) | $3.152 \times 10^{-5}$ | $3.177 \times 10^{-4}$ | $1.137 \times 10^{-3}$ | $2.140 \times 10^{-3}$ | $4.112 \times 10^{-3}$ | $6.341 \times 10^{-3}$ | $8.961 \times 10^{-3}$ | $1.070 \times 10^{-2}$ | $1.159 \times 10^{-2}$ | $1.161 \times 10^{-2}$ | $1.207 \times 10^{-2}$ | | $1.207 \times 10^{-2}$ |
| I | Cumulative Percent of Mass | 0.26 | 2.63 | 9.42 | 17.73 | 34.04 | 52.55 | 74.26 | 88.67 | 96.05 | 96.21 | 100 | | |

drop spectra counts. Again, a minimum of 200 stains should be counted and sized using a procedure similar to the procedure described in Section 5.1 for obtaining drop densities, except that the measuring magnifier is used to size stains and classify them according to size intervals. After the card and template have been secured to the cork board with push pins, the magnifier is used to measure the drops in each column. Counting and sizing is best accomplished using two people, one to size drops and another to record each drop in terms of a size-category number on scratch paper. After the stains in each column are counted and sized, sum the number of stains in each category. When the counting and sizing of drops in all five columns of the selected area have been completed, the subtotals are added and the total number of stains in each size category entered on the form shown in Figure 5-4 for each card analyzed. The example calculations in Figure 5-4 for Card Number 43 show that 41 stains were counted in a 16 square-centimeter area of the template that were less than 100 $\mu$m in diameter, 118 stains were less than 200 $\mu$m and equal to or greater than 100 $\mu$m, etc. In the example, a total of 545 stains were counted on Card Number 43 in the 16 square-centimeter area of the template. The 8 square-centimeter area of the template could have been used and more than 200 stains counted. Note that the 8 square-centimeter area was used in analyzing the remaining four cards. The drop density for each size category is obtained by dividing the number of drops in the category by the template area used in the analysis. These drop densities are entered on the Drop Spectra Data sheet.

After all five cards have been analyzed, determination of the drop-size distribution parameters can proceed. For convenience in explaining the calculations, the rows used in these calculations on the Drop Spectra Data sheet have been identified by the letters A through I.

### Row A - Mean Drop Diameter

The volume mean drop diameter in each size category is calculated from the expression

$$\bar{d} = \left( \frac{d_2^3 + d_1^2 d_2 + d_1 d_2^2 + d_1^3}{4} \right)^{1/3} \qquad (5\text{-}2)$$

where

$d_1$ = drop lower limit for the size category

$d_2$ = drop upper limit for the size category

For example, the entry in the first column of Row A is calculated as

$$\bar{d} = \left[ \frac{(27.6)^3 + (17.6)^2\, 27.6 + 17.6\, (27.6)^2 + (17.6)^3}{4} \right]^{1/3}$$

$$= 23.0\, \mu m$$

Repeat the calculation for each size category and enter the result in the appropriate column of Row A.

Row B - Mean Drop Mass

The mean drop mass in milligrams for each size category is calculated from the relationship

$$\bar{m} = \frac{\pi \rho (\bar{d})^3}{6} \times 10^{-9} \qquad (5\text{-}3)$$

$$= 5.236 \times 10^{-10} \rho (\bar{d})^3$$

where

$\rho$ = density of spray material in grams per cubic centimeter

For the example shown in Figure 5-4, where the density of the spray material is 1.067 grams per cubic centimeter, the entry in the first column of Row B is

$$\bar{m} = 5.236 \times 10^{-10} (1.067) (23.0)^3$$

$$= 6.797 \times 10^{-6} \text{ milligrams}$$

Repeat the calculation for each size category and enter the result in the appropriate column of Row B.

Row C - Sum of Drop Densities by Size Category

The sum of drop densities by size category is obtained by summing the drop density in each size category over all the cards analyzed in the swath. In the example shown in Figure 5-4, the result for the first column in Row C is

$$2.562 + 5.500 + 8.625 + 5.500 + 1.000 = 23.187$$

$$= 23.19$$

where 2.562 is the drop density from Card 43, size category 1, 5.5 is the drop density from Card 46, size category 1, etc.

Repeat the summation procedure for each size category and enter the results in the appropriate column of Row C.

Row D - Average Drop Densities by Size Category

The average drop density in each size category is obtained by dividing the sum of drop densities in Row C by the number of cards included in the analysis (5 in this case). For the example shown in Figure 5-4, we thus obtain

$$\frac{23.19}{5} = 4.638$$

which should be entered in the first column of Row D for size category 1.

Repeat the calculation for each size category and enter the result in the appropriate column of Row D.

## Row E - Cumulative Drop Densities

The cumulative drop densities shown in Row E of Figure 5-4 were calculated from the average densities recorded in Row D. The cumulative density recorded in each size category column of Row E is the cumulative sum up to and including the average drop density recorded for that size category in Row D. For the example shown in Figure 5-4 in Row E for category size 3, the cumulative drop density is

$$4.638 + 8.976 + 7.362 = 20.976 = 20.98$$

Continue the summation procedure across Row D until the cumulative density for each size category has been calculated and recorded in the appropriate column of Row E. Also, enter the cumulative sum for the largest category (32.64 in Figure 5-4) in the total columns of Row E.

## Row F - Cumulative Percent of Drop Densities

The cumulative percent of drop densities is calculated for each size category by dividing the cumulative drop density for each category in Row E by the cumulative drop density in the Total Column of Row E and multiplying by 100. For the example in Figure 5-4, the cumulative percent in the first column of Row F for size category 1 is

$$\frac{4.638}{32.64} \times 100 = 14.21 \text{ percent}$$

Calculate the cumulative percent of drop densities for every size category and record the result in the appropriate column of Row F.

## Row G - Average Deposition by Size Category

The average mass deposition by size category is calculated by multiplying the mean drop mass in a given size category in Row B by the corresponding average drop density in Row D. Thus the average deposition for category 1 in Row G of Figure 5-4 was obtained from

$$(6.797 \times 10^{-6})(4.638) = 3.152 \times 10^{-5} \text{ milligrams per square centimeter}$$

Complete the calculation for each size category and enter the results in the appropriate column of Row G.

## Row H - Cumulative Mass

The cumulative mass for each size category shown in Row H of Figure 5-4 is calculated from the average deposition values recorded in Row G. The cumulative mass recorded in each size category column of Row H is the cumulative sum up to and including the average deposition recorded for that size category in Row G. For the example shown in Figure 5-4 in Row H for size category 3, the cumulative mass is

$$3.125 \times 10^{-5} + 2.862 \times 10^{-4} + 8.194 \times 10^{-4} = 1.137 \times 10^{-3}$$

Continue the summation procedure across Row G until the cumulative mass for each size category has been calculated and recorded in the appropriate column of Row H. Also enter the cumulative sum for the largest category ($1.207 \times 10^{-2}$ in Figure 5-1) in the Total column for Row H.

## Row I - Cumulative Percent of Mass

The cumulative percent of mass is calculated for each size category by dividing the cumulative mass for each category in Row H by the cumulative mass in the Total column of Row H and multiplying by 100. For the example shown in Figure 5-4, the cumulative percent in the first column of Row I for size category 1 is

$$\frac{3.152 \times 10^{-5}}{1.207 \times 10^{-2}} \times 100 = 0.26 \text{ percent}$$

Calculate the cumulative percent of mass for each size category and record the result in the appropriate column of Row I.

## Mass and Volume Median Diameter

The mass median diameter is the drop diameter that divides the spray deposition distribution into two equal parts by mass. Thus, 50 percent of the mass deposited in the swath is due to deposition from drops with diameters greater than the mass median diameter and 50 percent is due to deposition from drops with diameters less than the mass median diameter. The mass median diameter is obtained from a graph of the cumulative percent of mass from Row I of Figure 5-4 plotted as a function of the drop upper limit for the size category on logarithmic probability paper.

Figure 5-5 shows the example distribution from Row I of Figure 5-4 plotted on 2-cycle log probability paper. The first point at the lower left of Figure 5-5 corresponds to a cumulative percent of mass of 0.26 percent from Row I and size category 1, where the drop upper limit is 27.6 $\mu$m. After all the points are plotted for cumulative percentages less than about 95 percent, connect the points on the graph. The mass median diameter is the diameter where the mass distribution curve intersects the 50-percent line on the plot. As shown in Figure 5-5, the mass median diameter for the example is about 125 $\mu$m. Since the mass and volume median diameters are equivalent (density is linear with drop size), the volume median diameter is also 125 $\mu$m.

## Average Mass Diameter

The average mass diameter (AMD) is calculated from the expression

$$AMD = 10^3 \left( \frac{6\ \bar{D}}{\pi \rho\ \bar{N}_D} \right)^{1/3}$$

$$AMD = 1.2407 \times 10^3 \left( \frac{\bar{D}}{\rho\ \bar{N}_D} \right)^{1/3} \qquad (5\text{-}4)$$

where

$\bar{D}$ = Total cumulative mass deposited on all cards from the Total column of Row H in Figure 5-4

$\bar{N}_D$ = Total cumulative drop density of all cards from the Total column of Row E in Figure 5-4

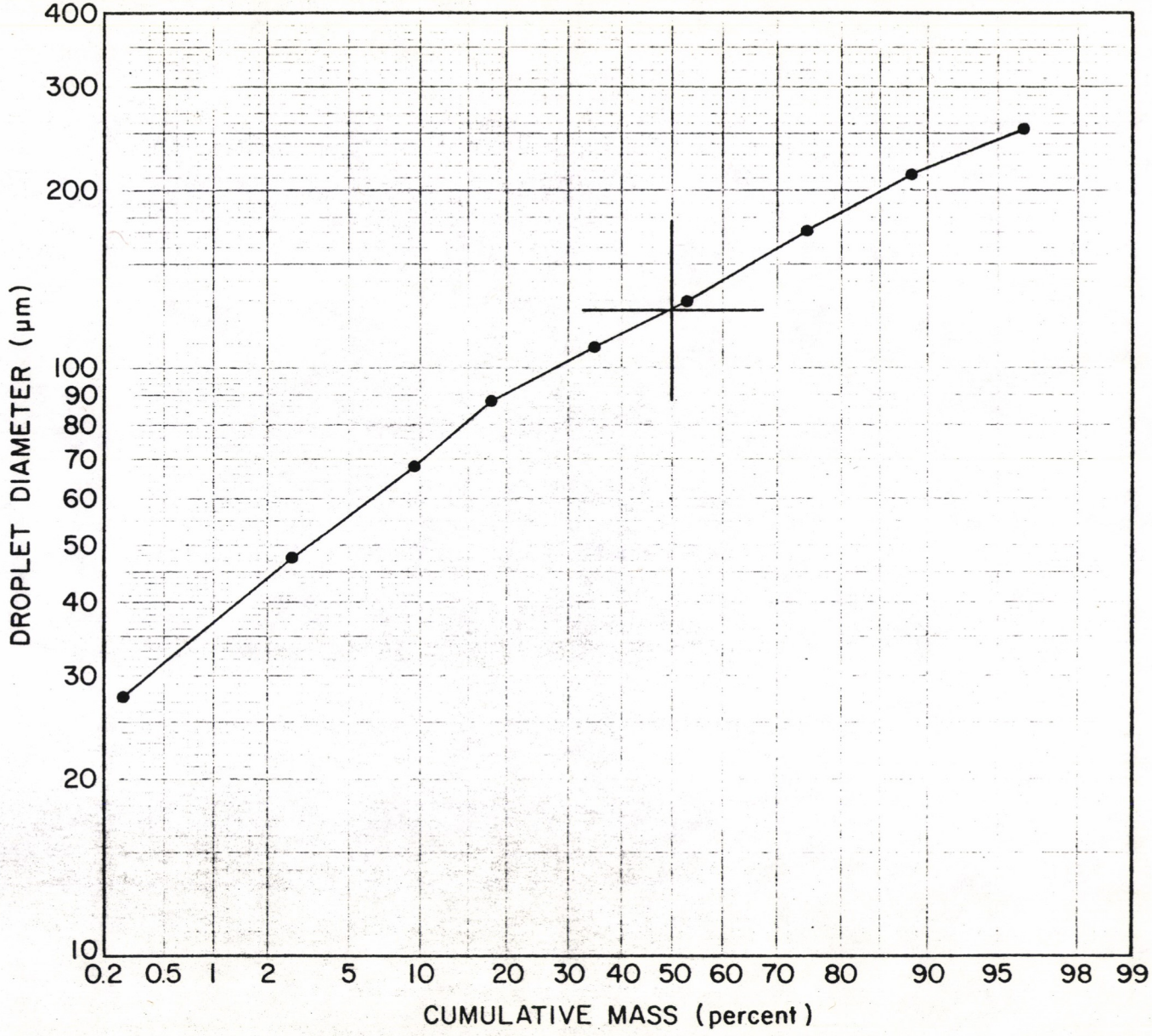



FIGURE 5-5. Cumulative mass distribution for the example trial. The symbol + marks the median of the cumulative mass distribution.

Thus, for the example distribution in Figure 5-4

$$AMD = 1.2407 \times 10^{3} \left[ \frac{1.207 \times 10^{-2}}{(1.067)(32.64)} \right]^{1/3}$$

$$= 87 \mu m$$

## Number Median Diameter

The number median diameter (NMD) is the drop diameter which divides the spray deposition distribution into two equal parts by number of drops counted. Thus, 50 percent of the total number of drops deposited in the swath have diameters greater than the number median diameter and 50 percent have diameters less than the number median diameter. The number median diameter is obtained from a graph of the cumulative percent of drop densities from Row F of Figure 5-4 as a function of the drop upper limit for the size category on logarithmic probability paper.

Figure 5-6 shows the example distribution from Row F of Figure 5-4 plotted on 2-cycle probability paper. The first point at the lower left of Figure 5-6 corresponds to a cumulative percent of drop densities of 14.21 percent from Row F and size category 1 where the drop upper limit is 27.6 $\mu$m. After all the points are plotted for cumulative percents less than about 95 percent, connect the points on the graph. The number median diameter is defined at the point where the number distribution curve intersects the 50-percent line on the plot. As shown by the + symbol in Figure 5-6, the number median diameter for the example is about 54 $\mu$m.

The preceeding calculations were performed using an electronic calculator with scientific notation, a memory and the capability of raising numbers to fractional powers. In Section 2, it was recommended that a desk-top programmable calculator

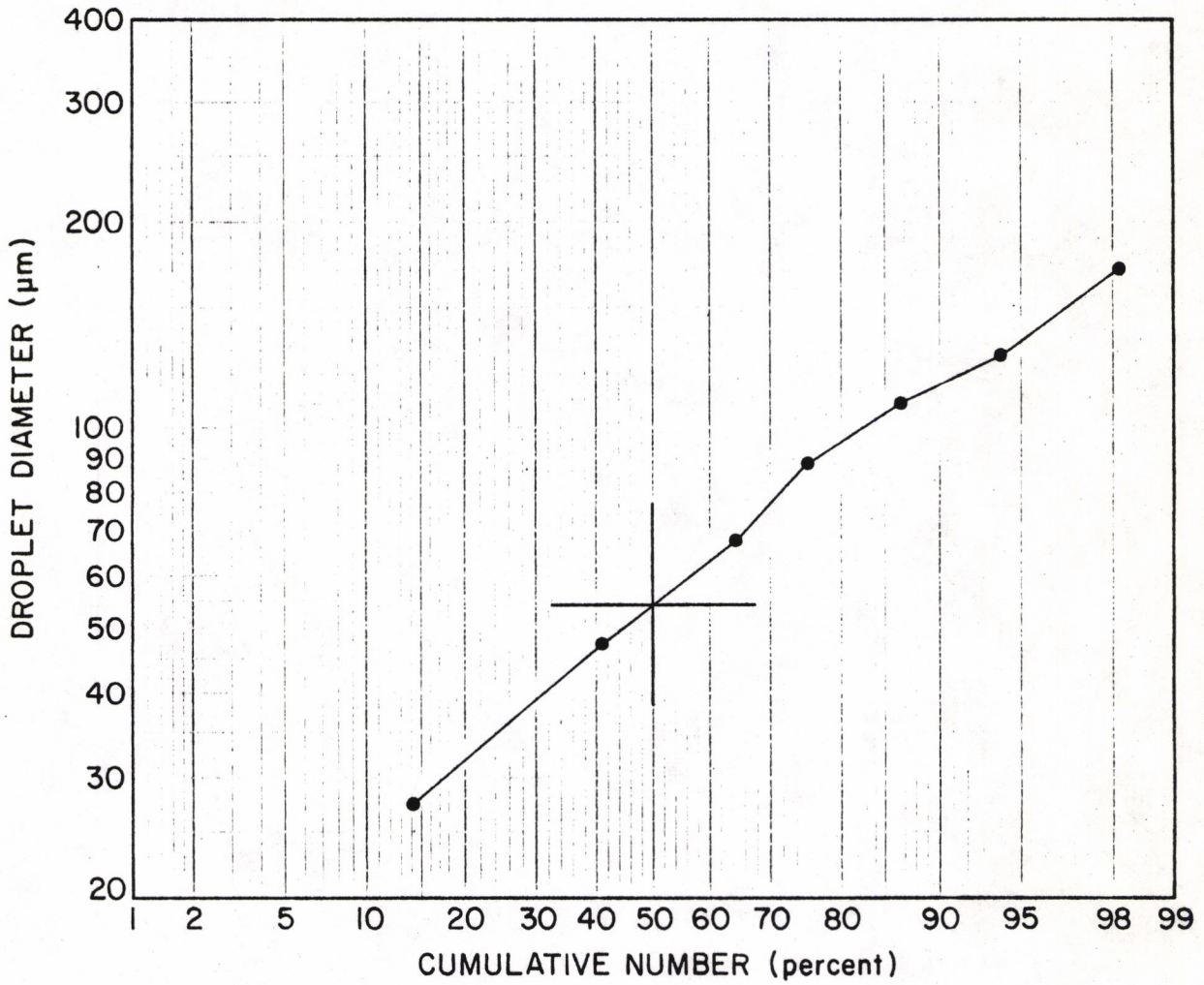



FIGURE 5-6. Cumulative number distribution for the example trial. The + symbol denotes the number median diameter.

be available for use by the field-project crew. If such a calculator were available, most or all of the calculations performed in this section could be completely automated so that an operator need only enter the material density, upper drop limits, card number, number of drops counted in each size category and the area counted. Automated calculation capabilities greatly reduce both the time required to complete the analysis and the chances that errors will be made in the analysis.

## 5.3 ESTIMATION OF SPRAY SYSTEM DEPOSITION, DEPOSITION EFFICIENCY (MASS RECOVERY) AND SWATH WIDTH BASED ON MASS DEPOSITION

The mean mass diameter calculated in Section 5.2 above, the drop density distribution in the swath from Figure 5-2, and the aircraft dissemination information can be used to estimate spray system deposition, mass recovery within the swath and deposition efficiency. Figure 5-7 is a copy of Figure 5-2 in Section 5.1, the Drop Density and Mass Deposition Data sheet, with data entered from the same trial used as an example in Section 5.2 for calculating swath parameters. The card numbers, template areas counted, number of stains counted and drop densities were entered in the form according to the procedures outlined in Section 5.1.

The deposition occurring on each card is obtained under the assumption that the mass distribution calculated in Section 5.2 is representative of the distribution on each card in the swath. Thus, the mean mass of all drops on the card is assumed to be

$$\overline{m} = 5.236 \times 10^{-10} \rho \, (AMD)^3 \qquad (5\text{-}5)$$

where AMD is the average mass diameter calculated from Equation (5-4).

For the example trial,

FIGURE 5-7

DROP DENSITY AND MASS DEPOSITION DATA

Trial Number 9 Average Mass Diameter 87.15 ($\mu$m)

Row Number C Mass $3.698 \times 10^{-4}$ (mg)

Conversion Factor: 1 oz. $acre^{-1}$ = $1.427 \times 10^{3}$ mg $cm^{-2}$

| Card Number | Template Area ($cm^2$) | Stain Count | Drop Density (drops $cm^{-2}$) | Deposition | |
|---|---|---|---|---|---|
| | | | | (mg $cm^{-2}$) | (oz. $acre^{-1}$) |
| 39 | 16 | 71 | 4.44 | $1.641 \times 10^{-3}$ | 2.342 |
| 40 | 16 | 130 | 8.13 | $3.005 \times 10^{-3}$ | 4.288 |
| 41 | 16 | 157 | 9.81 | $3.629 \times 10^{-3}$ | 5.178 |
| 42 | 16 | 304 | 19.00 | $7.026 \times 10^{-3}$ | 10.026 |
| 43 | 16 | 545 | 34.06 | $1.260 \times 10^{-2}$ | 17.975 |
| 44 | 8 | 297 | 37.13 | $1.373 \times 10^{-2}$ | 19.591 |
| 45 | 8 | 296 | 37.00 | $1.368 \times 10^{-2}$ | 19.525 |
| 46 | 8 | 243 | 30.38 | $1.123 \times 10^{-2}$ | 16.029 |
| 47 | 8 | 312 | 39.00 | $1.442 \times 10^{-2}$ | 20.580 |
| 48 | 8 | 323 | 40.38 | $1.493 \times 10^{-2}$ | 21.306 |
| 49 | 8 | 257 | 32.13 | $1.188 \times 10^{-2}$ | 16.952 |
| 50 | 8 | 267 | 33.38 | $1.234 \times 10^{-2}$ | 17.612 |
| 51 | 8 | 281 | 35.13 | $1.299 \times 10^{-2}$ | 18.535 |
| 52 | 8 | 317 | 39.63 | $1.465 \times 10^{-2}$ | 20.910 |
| 53 | 8 | 289 | 36.13 | $1.336 \times 10^{-2}$ | 19.063 |
| 54 | 8 | 318 | 39.75 | $1.470 \times 10^{-2}$ | 20.976 |
| 55 | 8 | 287 | 35.88 | $1.327 \times 10^{-2}$ | 18.931 |
| 56 | 8 | 258 | 32.25 | $1.193 \times 10^{-2}$ | 17.018 |
| 57 | 8 | 205 | 25.63 | $9.476 \times 10^{-3}$ | 13.522 |
| 58 | 16 | 184 | 11.50 | $4.253 \times 10^{-3}$ | 6.068 |
| Total | | | | .21474 | 306.427 |

Mass Recovery $5.6684 \times 10^{3}$ (mg $m^{-1}$)

Deposition Efficiency 18.66 (percent)

$$\bar{m} = 5.236 \times 10^{-10} (1.067) (87.15)^3$$

$$= 3.698 \times 10^{-4} \text{ mg}$$

This value is entered in the space provided for mass at the top of the form shown in Figure 5-7. The deposition on each card is then calculated by multiplying the mean mass $\bar{m}$ by the drop density for each card. For Card Number 42

$$19.00 \times 3.698 \times 10^{-4} = 7.026 \times 10^{-3} \text{ mg cm}^{-2}$$

Using the conversion factor to obtain ounces per acre, we obtain

$$7.026 \times 10^{-3} \frac{\text{mg}}{\text{cm}^2} \times 1.427 \times 10^{3} = 10.03 \frac{\text{ounces}}{\text{acre}}$$

The multiplication is completed for each card in the swath and the results entered on the data sheet.

The total mass recovery along the sampling line is calculated by summing the deposition from all cards in the swath and multiplying by the separation distance between cards. In this example, the card spacing was 10 feet (304.8 centimeters). The sum of the deposition is shown in the row labeled Total on the data sheet. Therefore, the total mass recovery along the sampling line is

$$.21474 \frac{\text{mg}}{\text{cm}^2} \times 304.8 \text{cm} = 65.453 \frac{\text{mg}}{\text{cm}}$$

or $6.5453 \times 10^3$ mg $m^{-1}$. The sampling line in this example case was not at right angles to the mean wind direction during the trial or to the flight path of the aircraft into the wind. Figure 5-8 is a schematic diagram showing that the wind direction was at an angle of 33 degrees with a line perpendicular to sampling line C. Therefore, the deposition integrated across the sampling line is greater than the mass recovered across the swath as represented by the dashed line at right angles to the wind direction in Figure 5-8. The corrected mass recovery is

$$6.5453 \times 10^3 \frac{mg}{m} \times \cos(33^\circ) = 5.6684 \times 10^3 \frac{mg}{m}$$

The deposition efficiency in the swath can be calculated using the mass recovery in the swath and the aircraft dissemination information. In the example trial, the aircraft was releasing 36.3 gallons of spray material per minute at an airspeed of 90 miles per hour. Converting these data into milligrams released per unit length of flight path, we obtain

$$18.15 \frac{gal}{min} \cdot \frac{hours}{90\ miles} \cdot \frac{mile}{1609.3m} \cdot \frac{60\ min}{hour} \cdot \frac{3785.43 cm^3}{gal} \cdot \frac{1.067g}{cm^3} \cdot \frac{10^3\ mg}{g}$$

$$= 3.037 \times 10^4\ mg\ m^{-1}$$

The deposition efficiency is then calculated to be

$$\frac{5.668 \times 10^3}{3.037 \times 10^4} \times 100 = 18.66 \text{ percent}$$

When the deposition producing pesticide effectiveness is known, the minimum effective swath width where deposition exceeds the effective deposition is easily de-

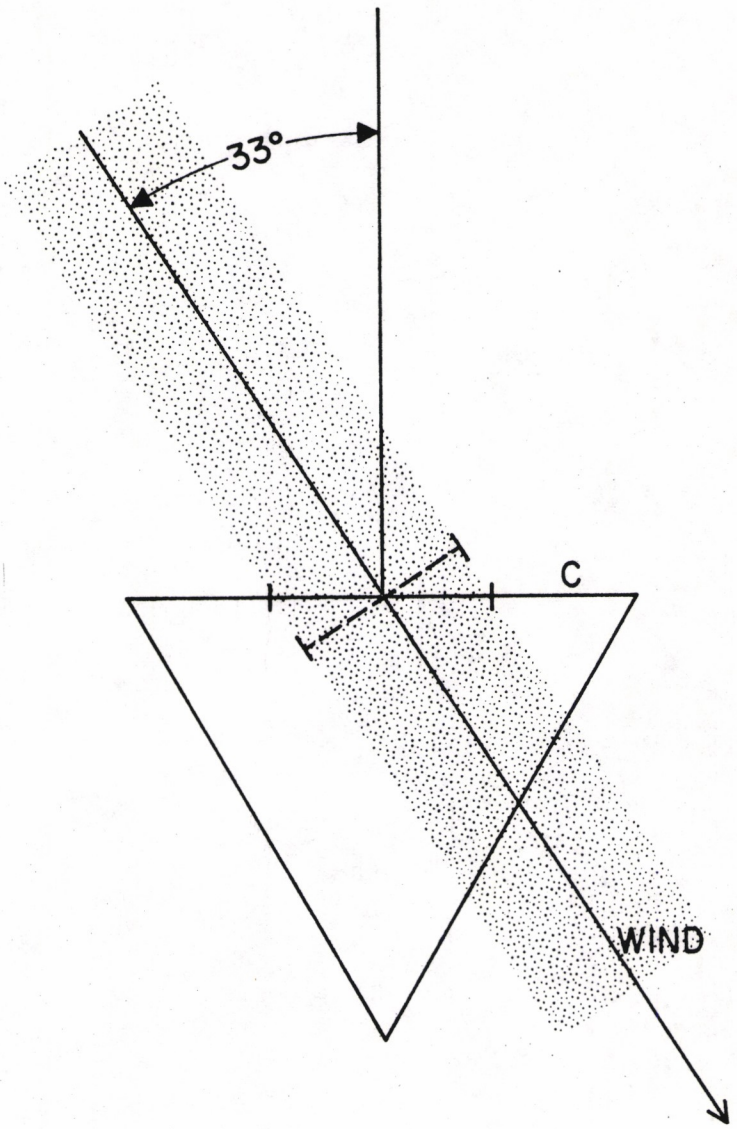



FIGURE 5-8. Schematic diagram showing wind direction with respect to sampling line C for the example trial.

termined from the information on the Drop Density and Mass Deposition Data sheet shown in Figure 5-7. A plot of the deposition shown in the table versus card number is given in Figure 5-9. For example, suppose the effective pesticide deposition is 60 ounces per acre. Since the samplers were separated by 10 feet in this trial, the effective swath width is

$$168 \text{ feet} \times \cos(33^{\circ}) = 145.5 \text{ feet}$$

after correction for the angle of wind direction with respect to the sampling line.

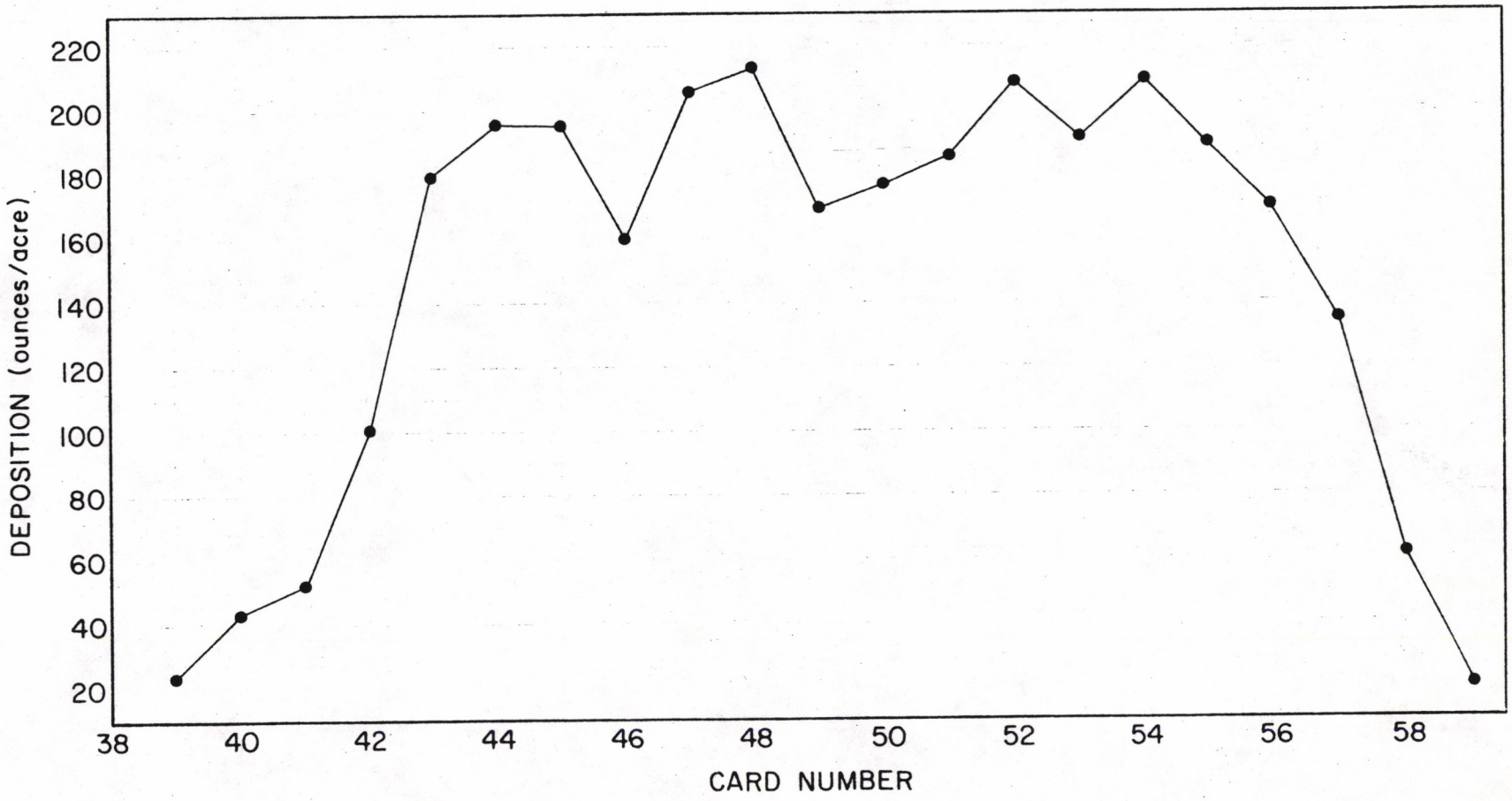



FIGURE 5-9. Deposition in ounces per acre across the sampling line for the example trial.

## REFERENCES

Morris, A. L., D. B. Call and R. B. McBeth, 1975: A small tethered balloon sounding system. Bulletin American Meteorological Society, Volume 56, Number 9, p. 964.

Maksymiuk, Bohdan, 1964: A rapid method for estimating the atomization of oil-base aerial sprays. Journal of Economic Entomology, Volume 57, No. 1, p. 16.

# APPENDIX B

## WIND MEASUREMENTS

Table B-1 contains a summary of 30-second average wind directions and wind speeds for the spray characterization trials conducted near Townsend, Montana. The measurements were made at a height of 2 meters using Beckman and Whitley sensors and Esterline-Angus recorders. Data from Trials 1, 4 and 8 were not analyzed. Only 5-minute average wind directions and speeds are given for Trials 2 and 3 because the recorders were operating at a low speed for these trials and more detailed estimates could not be made.

TABLE B-1

WIND MEASUREMENTS FOR THE TOWNSEND TRIALS

| Trial | Time (sec) | Wind Direction (degrees) | Wind Speed (mph) |
|---|---|---|---|
| 2 | 300 | 125 | 2.0 |
| 3 | 300 | 050 | 5.0 |
| 5 | 0 | 275 | 7.0 |
| | 30 | 280 | 8.0 |
| | 60 | 295 | 7.0 |
| | 90 | 290 | 7.5 |
| | 120 | 290 | 7.5 |
| | 150 | 290 | 7.5 |
| | 180 | 290 | 7.0 |
| | 210 | 285 | 7.0 |
| | 240 | 285 | 6.5 |
| | 270 | 285 | 6.5 |
| 6 | 0 | 295 | 3.0 |
| | 30 | 265 | 4.0 |
| | 60 | 245 | 4.5 |
| | 90 | 250 | 4.0 |
| | 120 | 250 | 3.0 |
| | 150 | 255 | 4.0 |
| | 180 | 255 | 4.0 |
| 7 | 0 | 100 | 2.5 |
| | 30 | 095 | 4.0 |
| | 60 | 100 | 3.5 |
| | 90 | 095 | 3.5 |

TABLE B-1 (Continued)

| Trial | Time (sec) | Wind Direction (degrees) | Wind Speed (mph) |
|---|---|---|---|
| 7 (Continued) | 120 | 100 | 3.5 |
| | 150 | 100 | 4.0 |
| | 180 | 115 | 3.5 |
| | 210 | 100 | 4.0 |
| | 240 | 105 | 3.5 |
| | 270 | 125 | 3.0 |
| 9 | 0 | 245 | 4.5 |
| | 30 | 240 | 5.0 |
| | 60 | 235 | 4.5 |
| | 90 | 240 | 4.5 |
| | 120 | 235 | 5.5 |
| | 150 | 235 | 5.0 |
| | 180 | 235 | 5.5 |
| | 210 | 235 | 4.5 |
| | 240 | 235 | 5.5 |
| | 270 | 235 | 5.0 |
| 10 | 0 | 260 | 5.5 |
| | 30 | 255 | 9.0 |
| | 60 | 265 | 6.0 |
| | 90 | 265 | 6.5 |
| | 120 | 265 | 6.0 |
| | 150 | 260 | 5.0 |
| | 180 | 245 | 4.0 |
| | 210 | 250 | 5.0 |
| | 240 | 250 | 5.0 |
| | 270 | 250 | 5.0 |

TABLE B-1 (Continued)

| Trial | Time (sec) | Wind Direction (degrees) | Wind Speed (mph) |
|---|---|---|---|
| 11 | 0 | 180 | 8.0 |
| | 30 | 175 | 9.5 |
| | 60 | 180 | 7.5 |
| | 90 | 185 | 8.0 |
| | 120 | 180 | 7.0 |
| | 150 | 170 | 6.5 |
| | 180 | 160 | 6.0 |
| | 210 | 160 | 6.0 |
| | 240 | 145 | 6.0 |
| | 270 | 150 | 6.0 |
| 12 | 0 | 050 | 2.5 |
| | 30 | 040 | 3.0 |
| | 60 | 035 | 3.0 |
| | 90 | 035 | 2.5 |
| | 120 | 025 | 2.0 |
| | 150 | 065 | 2.5 |
| | 180 | 145 | 3.5 |
| | 210 | 065 | 2.5 |
| | 240 | 040 | 2.5 |
| | 270 | 350 | 2.5 |
| 13 | 0 | 355 | 2.0 |
| | 30 | 330 | 2.0 |
| | 60 | 330 | 2.5 |
| | 90 | 310 | 2.0 |
| | 120 | 300 | 2.0 |
| | 150 | 305 | 2.0 |
| | 180 | 335 | 2.0 |
| | 210 | 005 | 2.0 |
| | 240 | 015 | 2.0 |
| | 270 | 330 | 2.0 |

TABLE B-1 (Continued)

| Trial | Time (sec) | Wind Direction (degrees) | Wind Speed (mph) |
|---|---|---|---|
| 14 | 0 | 225 | 5.0 |
| | 30 | 235 | 7.0 |
| | 60 | 230 | 7.0 |
| | 90 | 225 | 6.5 |
| | 120 | 220 | 6.5 |
| | 150 | 215 | 8.0 |
| | 180 | 210 | 6.5 |
| | 210 | 215 | 6.5 |
| | 240 | 220 | 7.5 |
| | 270 | 220 | 7.0 |
| 15 | 0 | 140 | 2.5 |
| | 30 | 145 | 5.5 |
| | 60 | 140 | 4.5 |
| | 90 | 140 | 4.0 |
| | 120 | 145 | 3.0 |
| | 150 | 140 | 2.5 |
| | 180 | 160 | 3.0 |
| | 210 | 170 | 2.5 |
| | 240 | 190 | 2.5 |
| | 270 | 200 | 2.0 |
| 16 | 0 | 145 | 8.0 |
| | 30 | 145 | 8.5 |
| | 60 | 135 | 6.5 |
| | 90 | 140 | 6.5 |
| | 120 | 130 | 5.5 |
| | 150 | 140 | 4.5 |
| | 180 | 140 | 5.5 |
| | 210 | 145 | 4.0 |
| | 240 | 140 | 4.0 |
| | 270 | 145 | 4.5 |

TABLE B-1 (Continued)

| Trial | Time (sec) | Wind Direction (degrees) | Wind Speed (mph) |
|---|---|---|---|
| 17 | 0 | 105 | 3.0 |
| | 30 | 115 | 3.5 |
| | 60 | 130 | 3.5 |
| | 90 | 125 | 3.0 |
| | 120 | 125 | 3.0 |
| | 150 | 125 | 3.0 |
| | 180 | 130 | 2.5 |
| | 210 | 125 | 2.5 |
| | 240 | 130 | 3.0 |
| | 270 | 120 | 3.0 |
| 18 | 0 | 105 | 7.5 |
| | 30 | 090 | 8.0 |
| | 60 | 095 | 9.0 |
| | 90 | 110 | 9.5 |
| | 120 | 110 | 8.0 |
| | 150 | 105 | 7.5 |
| | 180 | 105 | 8.0 |
| | 210 | 105 | 8.0 |
| | 240 | 120 | 9.0 |
| | 270 | 135 | 9.0 |
| 19 | 0 | 105 | 7.5 |
| | 30 | 105 | 8.0 |
| | 60 | 105 | 9.0 |
| | 90 | 100 | 9.5 |
| | 120 | 110 | 8.0 |
| | 150 | 100 | 7.5 |
| | 180 | 095 | 8.0 |
| | 210 | 115 | 8.0 |
| | 240 | 115 | 9.0 |
| | 270 | 120 | 9.0 |

# APPENDIX C

## FIELD LABORATORY ESTIMATES OF SPRAY DEPOSIT DENSITIES

This appendix contains a tabulation of spray deposit densities estimated for each card in the swath during 16 of the spray characterization trials conducted near Townsend, Montana. These estimates were made in the field laboratory at Townsend using procedures described in Section 2 of the main body of the report. No density estimates are presented for Trials 1, 4 and 8. The deposition data for Trial 1 were invalid because the helicopter spray system was not purged of water. Trial 4 was the last trial in a series of morning trials in which the elevated position of the cards relative to the ground caused the stains to be elongated making the analysis of spray characteristics other than spray deposit density difficult. Because the relatively high wind speed during Trial 4 increased the elongation of stains on the cards, the data were not analyzed. In Trial 8, the spray helicopter flew crosswind and the sampling grid was not adequate for estimating spray deposit densities in the swath.

TABLE C-1

SPRAY DEPOSIT DENSITIES FOR THE TOWNSEND SPRAY CHARACTERIZATION TRIALS

| Card Number | Drop Density ($Drops\ cm^{-2}$) |
|---|---|
| Trial 2 | |
| 57 | 3.1 |
| 58 | 15.6 |
| 59 | 15.6 |
| 60 | 35.9 |
| 61 | 25.0 |
| 62 | 30.6 |
| 63 | 26.6 |
| 64 | 23.1 |
| 65 | 15.6 |
| 66 | 18.1 |
| 67 | 25.6 |
| 68 | 19.4 |
| 69 | 14.1 |
| 70 | 17.2 |
| 71 | 18.8 |
| 72 | 21.9 |
| 73 | 18.1 |
| 74 | 21.9 |
| 75 | 16.9 |
| 76 | 18.1 |
| 77 | 17.2 |
| 78 | 18.8 |
| 79 | 7.8 |
| 80 | 4.1 |
| 81 | 4.7 |
| 82 | 5.6 |
| 83 | 6.9 |
| 84 | 6.9 |
| 85 | 4.7 |
| 86 | 5.9 |
| 87 | 4.7 |
| 88 | 7.5 |
| 89 | 6.3 |
| 90 | 6.9 |
| 91 | 6.9 |
| 92 | 8.1 |
| 93 | 6.9 |
| 94 | 5.6 |
| 95 | 4.7 |
| 96 | 6.3 |
| 97 | 4.4 |
| 98 | 3.4 |
| 99 | 4.7 |
| 100 | 4.4 |
| 101 | 3.4 |
| 102 | 4.7 |
| 103 | 4.4 |
| 104 | 4.1 |
| 105 | 3.4 |
| 106 | 3.1 |
| 107 | 3.1 |
| 108 | 3.1 |
| Trial 3 | |
| 51 | .4 |
| 52 | 13.8 |
| 53 | 31.3 |
| 54 | 17.2 |
| 55 | 23.4 |
| 56 | 14.1 |
| 57 | 15.6 |
| 58 | 20.3 |
| 59 | 18.1 |
| 60 | 28.1 |
| 61 | 25.0 |
| 62 | 25.0 |
| 63 | 20.3 |
| 64 | 24.4 |
| 65 | 20.3 |
| 66 | 14.1 |
| 67 | 25.0 |
| 68 | 13.1 |
| 69 | 8.1 |
| 70 | 12.5 |
| 71 | 4.7 |
| 72 | 5.0 |
| 73 | 8.1 |
| 74 | 5.0 |
| 75 | 6.9 |
| 76 | 7.5 |
| 77 | 4.7 |
| Trial 5 | |
| 56 | 3.1 |
| 57 | 17.2 |
| 58 | 28.1 |
| 59 | 42.2 |
| 60 | 21.9 |
| 61 | 35.9 |
| 62 | 21.9 |
| 63 | 17.2 |
| 64 | 25.0 |
| 65 | 25.2 |
| 66 | 28.1 |
| 67 | 23.4 |
| 68 | 23.4 |
| 69 | 31.2 |
| 70 | 25.0 |
| 71 | 28.1 |
| 72 | 21.9 |
| 73 | 21.9 |
| 74 | 21.9 |
| 75 | 28.1 |

TABLE C-1 (Continued)

| Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|
| 76 | 20.3 |
| 77 | 20.3 |
| 79 | 17.2 |
| 80 | 21.9 |
| 81 | 20.3 |
| 82 | 14.7 |
| **Trial 6** | |
| 37 | 4.4 |
| 38 | 5.0 |
| 39 | 3.8 |
| 40 | 4.4 |
| 41 | 3.4 |
| 42 | 2.8 |
| 43 | 4.4 |
| 44 | 2.2 |
| 45 | 5.0 |
| 46 | 5.0 |
| 47 | 5.3 |
| 48 | 3.8 |
| 49 | 4.1 |
| 50 | 5.6 |
| 51 | 3.4 |
| 52 | 4.7 |
| 53 | 9.1 |
| 54 | 14.4 |
| 55 | 14.4 |
| 56 | 9.1 |
| 57 | 20.6 |
| 58 | 29.1 |
| 59 | 39.1 |
| 60 | 26.6 |
| 61 | 25.0 |
| 62 | 28.1 |
| 63 | 26.2 |
| 64 | 21.9 |
| 65 | 12.5 |
| 66 | 11.9 |
| 67 | 13.8 |
| 68 | 16.6 |
| 69 | 12.5 |
| 70 | 8.8 |
| **Trial 7** | |
| 67 | 3.1 |
| 66 | 3.8 |
| 67 | 3.1 |
| 68 | 3.1 |
| 69 | 3.1 |
| 70 | 7.2 |
| 71 | 9.4 |
| 72 | 6.9 |
| 73 | 12.5 |
| 74 | 12.5 |
| 75 | 12.5 |
| 76 | 15.6 |
| 77 | 15.6 |
| 78 | 15.6 |
| 79 | 18.8 |
| 80 | 15.6 |
| 81 | 11.6 |
| 82 | 14.1 |
| 83 | 20.3 |
| 84 | 17.2 |
| 85 | 11.9 |
| 86 | 13.1 |
| 87 | 12.5 |
| 88 | 20.3 |
| 89 | 20.3 |
| 90 | 22.5 |
| 91 | 19.4 |
| 92 | 24.1 |
| 93 | 16.3 |
| 94 | 16.6 |
| 95 | 11.3 |
| 96 | 14.1 |
| 97 | 13.8 |
| 98 | 14.1 |
| 99 | 13.4 |
| 100 | 14.1 |
| 101 | 11.9 |
| 102 | 10.9 |
| 103 | 14.7 |
| 104 | 12.5 |
| 105 | 11.9 |
| 106 | 10.6 |
| 107 | 16.6 |
| 108 | 11.6 |
| 109 | 7.8 |
| 110 | 4.4 |
| 111 | 6.3 |
| 112 | 3.8 |
| **Trial 9** | |
| 37 | 2.5 |
| 38 | 3.1 |
| 39 | 6.6 |
| 40 | 6.9 |
| 41 | 8.1 |
| 42 | 17.2 |
| 43 | 33.1 |
| 44 | 37.5 |

TABLE C-1 (Continued)

| Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|
| 45 | 34.4 |
| 46 | 30.0 |
| 47 | 41.9 |
| 48 | 48.4 |
| 49 | 36.3 |
| 50 | 36.9 |
| 51 | 35.3 |
| 52 | 41.6 |
| 53 | 41.6 |
| 54 | 42.5 |
| 55 | 36.3 |
| 56 | 32.2 |
| 57 | 26.6 |
| 58 | 11.9 |
| 59 | 7.2 |
| 60 | 2.8 |
| 61 | 1.9 |
| Trial 10 | |
| 49 | 6.3 |
| 50 | 10.9 |
| 51 | 13.4 |
| 52 | 20.3 |
| 53 | 20.3 |
| 54 | 29.7 |
| 55 | 29.4 |
| 56 | 43.8 |
| 57 | 38.1 |
| 58 | 48.4 |
| 59 | 48.4 |
| 60 | 50.6 |
| 61 | 53.1 |
| 62 | 48.1 |
| 63 | 51.9 |
| 64 | 56.3 |
| 65 | 40.6 |
| 66 | 44.7 |
| 67 | 26.6 |
| 68 | 34.1 |
| 69 | 30.0 |
| 70 | 33.1 |
| 71 | 20.3 |
| 72 | 26.6 |
| 73 | 18.1 |
| 74 | 15.6 |
| 75 | 17.8 |
| 76 | 15.0 |
| 77 | 13.1 |
| 78 | 10.3 |
| 79 | 16.3 |
| 80 | 11.3 |
| 81 | 10.0 |
| 82 | 11.2 |
| 83 | 11.2 |
| 84 | 8.8 |
| 85 | 8.8 |
| 86 | 6.9 |
| 87 | 7.8 |
| 88 | 7.2 |
| 89 | 5.6 |
| 90 | 5.9 |
| 91 | 7.2 |
| 92 | 7.2 |
| Trial 11 | |
| 10 | 6.3 |
| 11 | 8.4 |
| 12 | 10.3 |
| 13 | 12.2 |
| 14 | 19.4 |
| 15 | 17.2 |
| 16 | 13.1 |
| 17 | 19.7 |
| 18 | 25.0 |
| 19 | 18.1 |
| 20 | 17.8 |
| 21 | 29.7 |
| 22 | 27.5 |
| 23 | 24.1 |
| 24 | 30.3 |
| 25 | 21.3 |
| 26 | 28.1 |
| 27 | 25.9 |
| 28 | 28.1 |
| 29 | 33.4 |
| 30 | 33.8 |
| 31 | 33.8 |
| 32 | 33.1 |
| 33 | 28.1 |
| 34 | 27.5 |
| 35 | 34.4 |
| 36 | 31.3 |
| 37 | 33.4 |
| 38 | 6.3 |
| Trial 12 | |
| 28 | 6.3 |
| 29 | 6.9 |
| 30 | 4.4 |
| 31 | 3.1 |
| 32 | 2.8 |
| 33 | 2.8 |
| 34 | 6.3 |
| 35 | 10.9 |
| 36 | 11.9 |

TABLE C-1 (Continued)

| Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|
| 37 | 11.3 |
| 38 | 12.5 |
| 39 | 14.1 |
| 40 | 11.9 |
| 41 | 8.4 |
| 42 | 15.9 |
| 43 | 13.8 |
| 44 | 10.3 |
| 45 | 19.4 |
| 46 | 17.2 |
| 47 | 21.9 |
| 48 | 16.6 |
| 49 | 16.6 |
| 50 | 16.9 |
| 51 | 20.0 |
| 52 | 14.1 |
| 53 | 20.3 |
| 54 | 30.0 |
| 55 | 35.0 |
| 56 | 34.4 |
| 57 | 43.8 |
| 58 | 44.4 |
| 59 | 45.3 |
| 60 | 23.1 |
| 61 | 20.0 |
| 62 | 17.1 |
| 63 | 20.3 |
| 64 | 20.6 |
| 65 | 11.9 |
| 66 | 11.9 |
| **Trial 13** | |
| 61 | 9.4 |
| 62 | 11.6 |
| 63 | 13.1 |

| Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|
| 64 | 17.5 |
| 65 | 12.5 |
| 66 | 16.3 |
| 67 | 21.9 |
| 68 | 32.8 |
| 69 | 38.1 |
| 70 | 38.8 |
| 71 | 29.1 |
| 72 | 13.1 |
| 73 | 13.4 |
| 74 | 14.1 |
| 75 | 16.3 |
| 76 | 13.1 |
| 77 | -- |
| 78 | 12.5 |
| 79 | 10.6 |
| 80 | 9.4 |
| 81 | 9.4 |
| 82 | 4.7 |
| 83 | 8.8 |
| 84 | 9.1 |
| 85 | 10.6 |
| 86 | 10.3 |
| 87 | 7.8 |
| 88 | 9.4 |
| 89 | 7.8 |
| 90 | 4.7 |
| 91 | 3.1 |
| 92 | 3.4 |
| 93 | 3.8 |
| **Trial 14** | |
| 27 | 6.3 |
| 28 | 3.4 |
| 29 | 6.9 |

| Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|
| 30 | 10.0 |
| 31 | 10.0 |
| 32 | 7.2 |
| 33 | 12.5 |
| 34 | 16.2 |
| 35 | 18.1 |
| 36 | 11.9 |
| 37 | 11.9 |
| 38 | 25.0 |
| 39 | 27.2 |
| 40 | 20.0 |
| 41 | 20.0 |
| 42 | 28.8 |
| 43 | 26.3 |
| 44 | 20.3 |
| 45 | 18.8 |
| 46 | 18.1 |
| 47 | 29.7 |
| 48 | 31.3 |
| 49 | 28.1 |
| 50 | 32.2 |
| 51 | 31.9 |
| 52 | 28.1 |
| 53 | 21.9 |
| 54 | 18.8 |
| 55 | 9.4 |
| 56 | 5.3 |
| **Trial 15** | |
| 55 | 7.8 |
| 56 | 11.6 |
| 57 | 15.6 |
| 58 | 36.2 |
| 59 | 32.8 |
| 60 | 43.8 |

TABLE C-1 (Continued)

| Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|
| 61 | 50.0 |
| 62 | 45.3 |
| 63 | 50.0 |
| 64 | 50.0 |
| 65 | 57.8 |
| 66 | 53.1 |
| 67 | 59.4 |
| 68 | 56.3 |
| 69 | 35.6 |
| 70 | 20.3 |
| 71 | 16.3 |
| 72 | 13.8 |
| 73 | 16.9 |
| 74 | 4.6 |
| 75 | 7.8 |
| **Trial 16** | |
| 57 | 3.1 |
| 58 | 9.4 |
| 59 | 15.0 |
| 60 | 23.8 |
| 61 | 28.1 |
| 62 | 42.2 |
| 63 | 46.9 |
| 64 | 40.6 |
| 65 | 37.5 |
| 66 | 34.4 |
| 67 | 31.3 |
| 68 | 39.1 |
| 69 | 33.8 |
| 70 | 21.9 |
| 71 | 9.4 |
| 72 | 19.7 |
| 73 | 14.1 |
| 74 | 17.8 |
| 75 | 15.0 |
| 76 | 16.9 |
| 77 | 13.8 |
| 78 | 7.8 |
| 79 | 4.7 |
| **Trial 17** | |
| 35 | 17.2 |
| 36 | 18.8 |
| 37 | 19.7 |
| 38 | 25.6 |
| 39 | 21.3 |
| 40 | 34.4 |
| 41 | 37.5 |
| 42 | 34.4 |
| 43 | 31.3 |
| 44 | 38.1 |
| 45 | 30.0 |
| 46 | 31.3 |
| 47 | 25.9 |
| 48 | 31.3 |
| 49 | 34.4 |
| 50 | 34.4 |
| 51 | 32.5 |
| 52 | 40.6 |
| 53 | 40.0 |
| 54 | 40.6 |
| 55 | 32.5 |
| 56 | 33.1 |
| 57 | 32.5 |
| 58 | 38.8 |
| 59 | 31.3 |
| 60 | 35.6 |
| 61 | 36.9 |
| 62 | 43.8 |
| 63 | 25.9 |
| 64 | 14.7 |
| **Trial 18** | |
| 41 | 6.6 |
| 42 | 12.2 |
| 43 | 11.3 |
| 44 | 11.6 |
| 45 | 18.8 |
| 46 | 21.3 |
| 47 | 16.3 |
| 48 | 22.5 |
| 49 | 21.9 |
| 50 | 28.8 |
| 51 | 28.1 |
| 52 | 32.8 |
| 53 | 28.1 |
| 54 | 40.0 |
| 55 | 40.6 |
| 56 | 25.9 |
| 57 | 29.7 |
| 58 | 35.3 |
| 59 | 41.6 |
| 60 | 37.5 |
| 61 | 42.5 |
| 62 | 38.8 |
| 63 | 45.3 |
| 64 | 58.1 |
| 65 | 38.1 |
| 66 | 31.9 |
| 67 | 3.8 |

TABLE C-1 (Continued)

| Card Number | Drop Density (Drops $cm^{-2}$) | Card Number | Drop Density (Drops $cm^{-2}$) | Card Number | Drop Density (Drops $cm^{-2}$) |
|---|---|---|---|---|---|
| Trial 19 | | | | | |
| 50 | 2.5 | | | | |
| 51 | 4.1 | | | | |
| 52 | 5.3 | | | | |
| 53 | 8.1 | | | | |
| 54 | 15.6 | | | | |
| 55 | 11.2 | | | | |
| 56 | 8.1 | | | | |
| 57 | 12.5 | | | | |
| 58 | 14.7 | | | | |
| 59 | 12.5 | | | | |
| 60 | 18.1 | | | | |
| 61 | 14.7 | | | | |
| 62 | 15.6 | | | | |
| 63 | 16.3 | | | | |
| 64 | 14.1 | | | | |
| 65 | 15.6 | | | | |
| 66 | 12.6 | | | | |
| 67 | 15.6 | | | | |
| 68 | 6.9 | | | | |
| 69 | 3.1 | | | | |
| 70 | 1.3 | | | | |